CONCEPTUAL STUDY
OF
ARTICULATED STABLE OCEAN PLATFORM

FINAL REPORT
PART I

CONTRACT NO. N00167-95-C-0113
CDRL SEQUENCE NO. G005

PREPARED FOR

CARDEROCK DIVISION
NAVAL SURFACE WARFARE CENTER

Prepared by

McDermott Engineering Houston. L.L.C.
801 N. Eldridge Street
Houston, Texas 77079

MEH Project 44271

May 6, 1997

19970605 140

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) MEH Project 44271	5. MONITORING ORGANIZATION REPORT NUMBER(S) CD/NSWC MSSPO (102) CR-96/03
6a. NAME OF PERFORMING ORGANIZATION McDermott Engineering Houston LLC 6b. OFFICE SYMBOL *(if applicable)*	7a. NAME OF MONITORING ORGANIZATION Naval Surface Warfare Center, Carderock Division
6c. ADDRESS *(City, State, and ZIP Code)* 801 North Eldridge Street Houston, TX 77079	7b. ADDRESS *(City, State, and ZIP Code)* 9500 MacArthur Boulevard West Bethesda, MD 20817-5700
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Defense Advanced Research Projects Agency 8b. OFFICE SYMBOL *(if applicable)* TTO	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00167-95-C-0113
8c. ADDRESS *(City, State, and ZIP Code)* 3701 North Fairfax Drive Arlington, VA 22203-1714	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 9750400 PROJECT NO.: TASK NO.: WORK UNIT ACCESSION NO.:

11. TITLE *(Include Security Classification)*

(U) Conceptual Study of Articulated Stable Ocean Platform

12. PERSONAL AUTHOR(S)

Trevor R.J. Mills and Zhihuang (Alex) Ran

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final	FROM 10/29/95 TO 11/27/96	1996 September 25	112

16. SUPPLEMENTARY NOTATION

Final Report - Part 1 (contains summary of concept and results)

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	articulated stable ocean platform, ASOP, floating production , offshore oil storage

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A conceptual study has been completed to evaluate the feasibility of a new concept of a floating storage platform - the Articulated Stable Ocean Platform (ASOP). The unique aspects of the ASOP is the articulation of the stabilize buoys which were introduced for the purposes of reducing wave load and overall vessel motion. The ASOP was designed to have a fuel storage capability of 1 million barrels and to support a topside up to 12,000 kips in total weight. The fuel storage tanks were designed in such a way that the draft of the platform would remain unchanged at any loading condition without adjusting the ballast. This greatly simplified the operations and allowed the platform to continue other activities while loading and off-loading.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Keith R. McAllister	22b. TELEPHONE *(Include Area Code)* (301) 227-5430	22c. OFFICE SYMBOL NSWCCD 293

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

REPORT DOCUMENTATION PAGE 2

The study shows that the ASOP has adequate stability and satisfies the stability requirement of the certifying authorities. Both numerical analysis and model test showed that the ASOP offers exceptional motion response characteristics in all its degrees of freedom. In terms of platform motion response, the ASOP is capable of operating in more severe weather conditions than a conventional surface vessel type platform. A seven body (six buoys and the hull) coupled motion analysis in ocean environment was performed and results in general agreed with the model test. However, both numerical analysis and model tests showed that the articulated buoys have no clear advantage over fixed buoys in the global motion of the ASOP. The reduction of forces by using articulation did not significantly improve the motion of the platform. Furthermore, the analysis and model test showed that compared to the fixed buoy case, using articulations increased the slow drift motions of the ASOP in random waves. The study also indicated that the introduction of articulations complicated the hydrostatic stability of the platform. Damaged stability was the governing factor in determination of the size of the articulated buoys. In conclusion, this conceptual study indicated that the fuel storage ASOP is a viable concept. Its large storage capability and exceptional motion characteristics allow many applications both in civil and military purpose.

TABLE OF CONTENTS

PART I

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 General

The Articulated Stable Ocean Platform (ASOP) is a new concept of floating storage offshore platform. It consists of the following basic components:

1) A hexagonal shape hull submerged in the water for fuel storage and ballast water;
2) Six surface-piercing buoys provide the stability for the platform. The buoys are cylindrical shaped and are attached to each corner of the hexagonal hull by means of universal joints;
3) A topside platform which houses the prime movers, pumps, mooring machinery, handing equipment and the payload supports, etc.;
4) A column located at the center of the hull supporting the topside. It also provides access to the lower hull and serves as an enclosure for piping, machinery, hawser pipes, etc.

Figure 1.1 shows the general arrangement of the ASOP. During deployment, the ASOP is towed to the site with its hull floating on the surface. The articulated buoys are secured in a horizontal position on the top of the hull. Upon arrival in the designated area, the ASOP is moored in a six-point mooring system. The articulated columns are rendered operable and the tanks in the hull are flooded to submerge the main hull to its prescribed draft. The buoys provide stability during the submerging evolution.

The ASOP has a geometry that is substantially different from the conventional ship, or other monohull platforms, such as FPSO (Floating Production, Storage and Off loading Platform). The geometry leads to hydrostatic and hydrodynamic behavior that is significantly different in its principles of operation. Because a large proportion of its submerged volume (hull) is at a deep draught where dynamic pressures have rapidly decayed with depth, the ASOP possesses low wave-induced motions. The small water plane area and the large submerged volume of the platform yield long natural periods in heave, roll and pitch. These periods are well above the periods of predominant wave action, further contributing to a reduction of the motion. By using articulation and allowing the buoys to rotate in pitch and roll, forces and motions transmitted from the buoys to the hull are minimized. Therefore, the ASOP is a "stable" platform and is suitable for the offshore tasks which have high restrictions on motion, such as offshore oil drilling and production, fuel storage, or military use.

In addition to the favorable motion characteristics, the ASOP has other advantages over conventional floating vessel production units. The advantages are as follows:

1) Production and integral oil storage in the same unit; no need for pipelines, storage tankers, and associated single point moorings.
2) A specific water depth is not required other than the requirement that the water be sufficiently deep to preclude grounding.
3) Mobile - can be moved as required with minimum effort.
4) Accommodates deck loads as required for oil production and storage or others by varying structural dimensions.
5) Fuel storage is sufficiently deep to preclude danger of tank rupture and oil spillage from collision damage.

1.2 Scope of Work

In this conceptual study of the ASOP, our objective was to produce a conceptual design and evaluate this design by a combination of analytical engineering and physical model tank testing. The fundamental issues were to determine the overall motion of the vessel and the interaction behavior of the articulated buoys and hence prove the viability and benefits of the ASOP. The study included the following tasks:

1) Application investigation and hull configuration design
2) Hull scantlings and weight estimate
3) Verify intact and damage stability
4) Seakeeping analysis
5) Model test
6) Cost estimate

All the procedures and results of the analysis for the above tasks are documented in this report. The report consists of two parts. Part I includes the design and numerical analysis, and summary of model test results. Part II includes detailed model test description and test results.

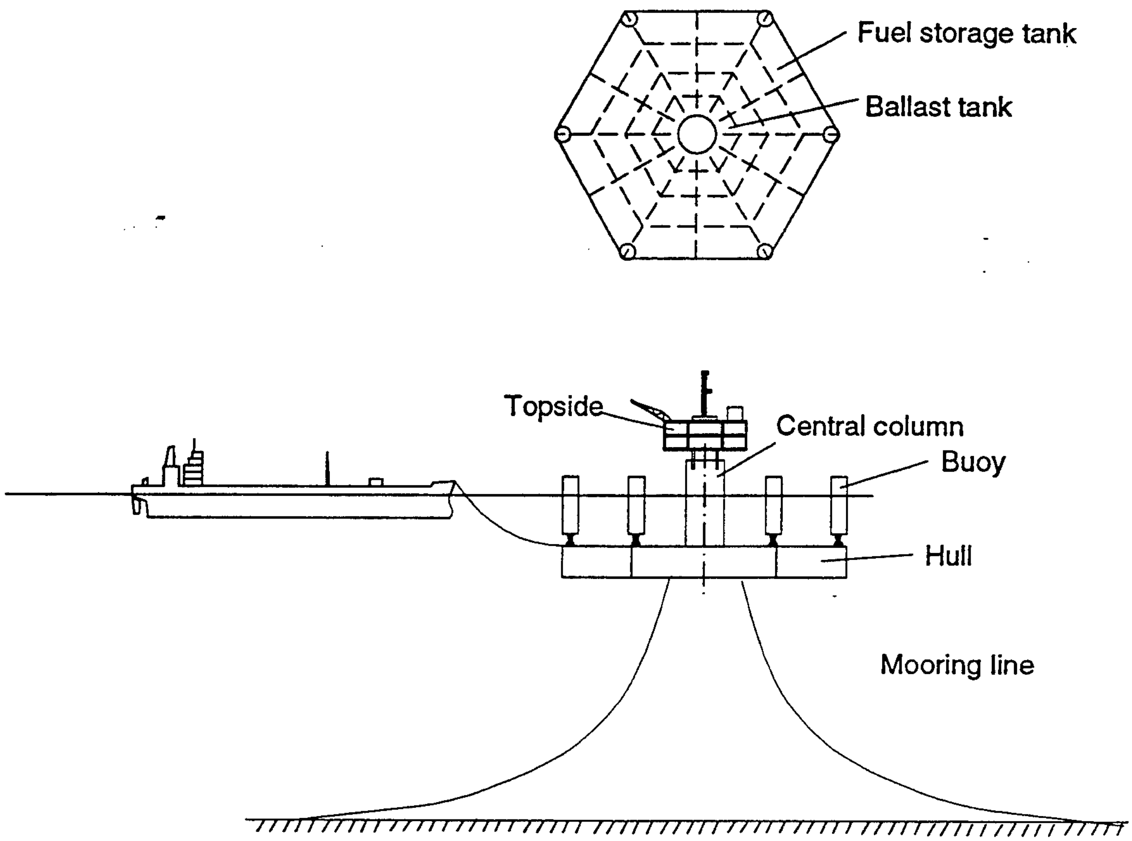


Figure 1.1 Articulated Stable Ocean Platform (ASOP)

CHAPTER 2 HULL CONFIGURATION

2.1 General

In this conceptual study stage, the military usage of the platform is not clear except for serving as a fuel storage and off-loading vessel, in which the topside hosts only fuel pumping equipment and has a small payload. Other applications of the platform may require higher payload on the topside. In this chapter, the configuration of the ASOP is determined based on its application in the offshore oil industry. The ASOP serves as an offshore oil production and fuel storage platform with a storage capacity of one million barrels. Figure 2.1 shows the configuration of the ASOP. The following sections describe the configuration design of the major components of the ASOP.

2.2 Topside

The topside weight may vary significantly depending on the applications and functions of the ASOP. It is the key factor to the stability of the platform due to its high level and it determines the configuration of hull and buoys. In this study, we estimated the topside and payload of the ASOP as an offshore fuel storage and production platform. The total weight of the topside is 12,000 kips, which includes the deck structural weight (2340 kips), fuel off-loading facilities, production and drill equipment and facilities (9660 kips). The center of gravity of the topside is 100 ft above waterline at the operational draft.

2.3 Hull

The total volume of the hull is determined by the fuel storage capacity and required ballast water. In our design, the hull has a hexagonal shape for simplicity. The hull height is 50 ft, and the distance across corners is 450 ft. The bottom of the hull is 145 ft below waterline. The tanks in the hull are divided into four ring shaped groups by four concentric hexagonal bulkheads. In each group, there are twelve tanks which are divided by the radial bulkheads. Figure 2.2 shows the dimension and compartmentation of the hull. The outer two groups of tanks are pressure compensated soft storage tanks, the "soft" means the structure of these tanks are not designed to take high hydrostatic pressure. The third group of tanks which is next to the soft tanks is pressure uncompensated hard storage tanks. The inner group of tanks is ballast tanks. The volume of the tanks is as follows:

Group	Volume (ft^3)
Soft tank 1	2.82×10^6
Soft tank 2	2.04×10^6
Hard tank	8.87×10^5
Ballast tank	6.90×10^5

The total capacity of fuel storage is 5.63×10^6 cubic feet, or about 1 million barrels. The total capacity of variable water ballast is 4.42×10^5 kips. When the platform needs to be relocated, the ballast water is pumped out to raise the hull near the water surface so that the soft tanks can be emptied at low pressure for transition. Unlike a tanker which has large variations of draft at different loading conditions due to the fuel weight change, the ASOP is designed to keep the operational draft at all loading conditions. In order to do so, the volume ratio of the soft tanks to hard tanks is designed to be 1 to 0.18. During loading (off-loading), the change of weight due to one barrel of fuel (water) displacing a like volume of sea water (fuel) in the soft tanks can be compensated by pumping 0.18 barrel fuel into (out of) the hard tanks displacing (replaced by) only air at the same time. Therefore, at any fuel loading condition, the total weight of the fluid (fuel and water) in the storage tanks is unchanged if the same 1 to 0.18 pumping ratio is maintained. The overall changes in the weight of the platform are handled by changing the amount of water in variable ballast tanks.

One of the concerns in the compartmentation of the hull is stability. In our design, the hull is compartmentalize in a way such that, when any one of the tanks in the hull is flooded, the platform will remain afloat with the topside above the water surface. The most severe situation is the flooding of one of the outmost soft tanks which is full of fuel. The gain of weight (2256 kips) by replacing fuel with sea water is not of serious concern, but the overturning moment create by the weight increase can cause a large heel. The damaged stability is further explained in Chapter 4.

2.4 Center Column

The center column is a cylindrical structure which is 60 ft in diameter and 150 ft long. The column has a free board of 55 ft at operational draft. The deck, which is mounted on the top of the center column, has a 70 ft air gap (vertical distance between waterline and the lowest deck structure) to avoid wave impact in a severe environmental condition. The column provides access to the lower hull and serves as an enclosure for piping and machinery, and more important, provides water plane area and reserved buoyancy for the stability of the platform. Figure 2.3 shows the dimensions and compartmentation of the center column.

2.5 Buoys

The six articulated buoys are cylindrical shaped and 30 ft in diameter and 85 ft long. The design draft of the buoys is 55 ft. Each buoy is located at the corner of the hexagonal hull to maximize the righting moment arm. At operational draft, the buoy has a net buoyancy of 1636 kips. At transit draft, the buoys are secured horizontally on top of the hull. Figure 2.4 shows the dimension and compartmentation of the buoy. The two radial bulkheads and two flats divide the buoys into 12 watertight compartments and limit the flooding volume when the buoy is damaged. Our damage stability analysis (in Chapter 4) indicates that flooding of four compartments at the same time will not jeopardize the platform.

2.6 Summary

The following are the principal characteristics of the ASOP:

Hull diameter (across corners)	450	ft
Hull height	50	ft
Center column diameter	60	ft
Center column height	150	ft
Buoy diameter	30	ft
Buoy length	85	ft
Transit draft	35	ft
Operational draft	145	ft

Buoy draft (operational)	55	ft
Topside weight	12,000	kips
Topside C.G.	245	ft above keel
Fuel storage	1	million barrel
Ballast water	442,000	kips
Displacement (transit)	294,622	kips
Displacement (operational)	452,865	kips

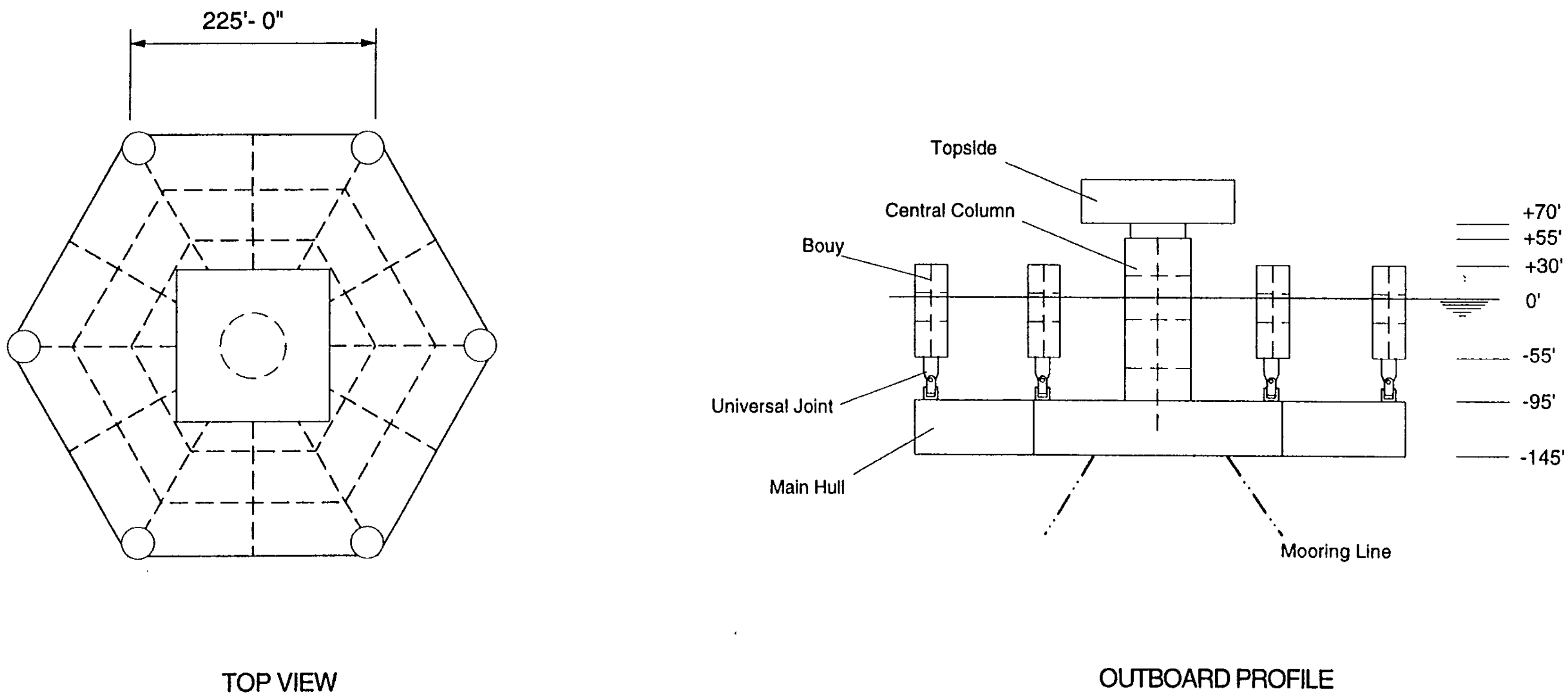


Figure 2.1 General arrangement of the ASOP

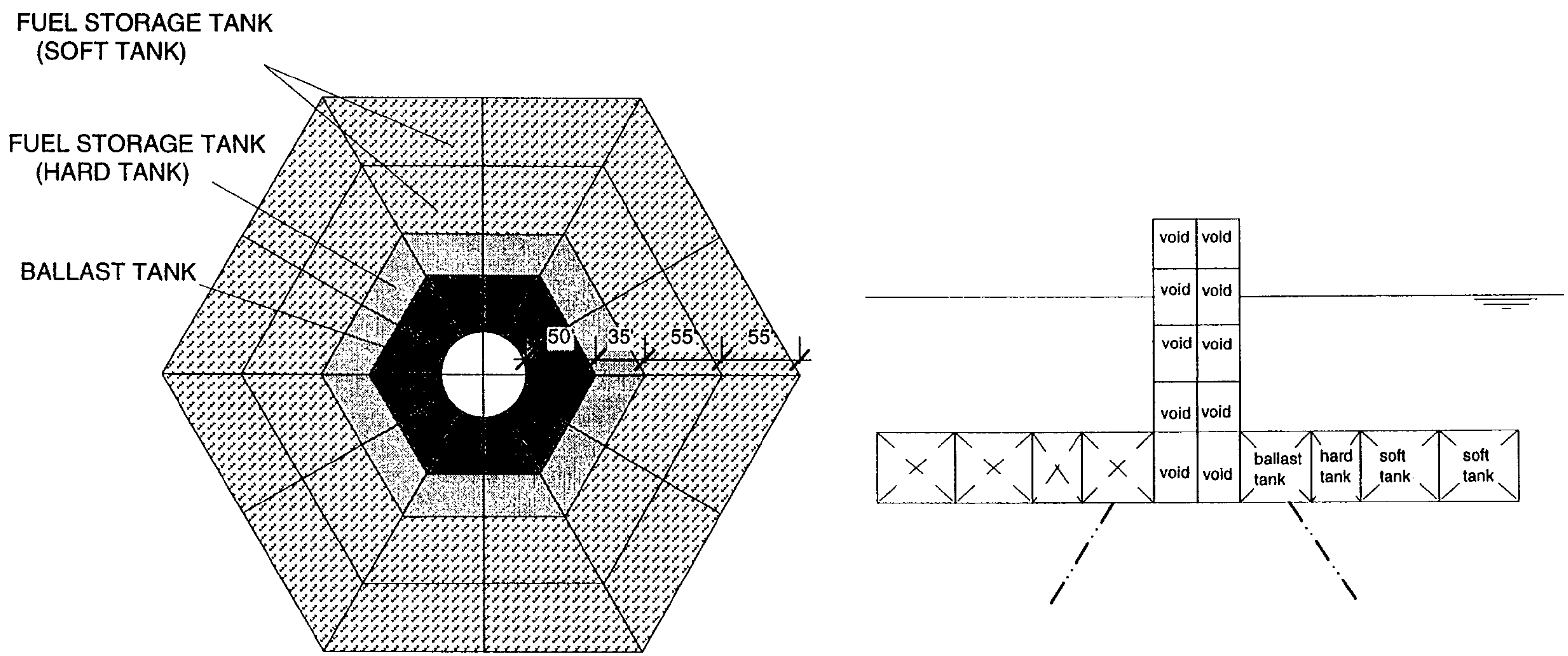


Figure 2.2 Compartmentation of the ASOP hull

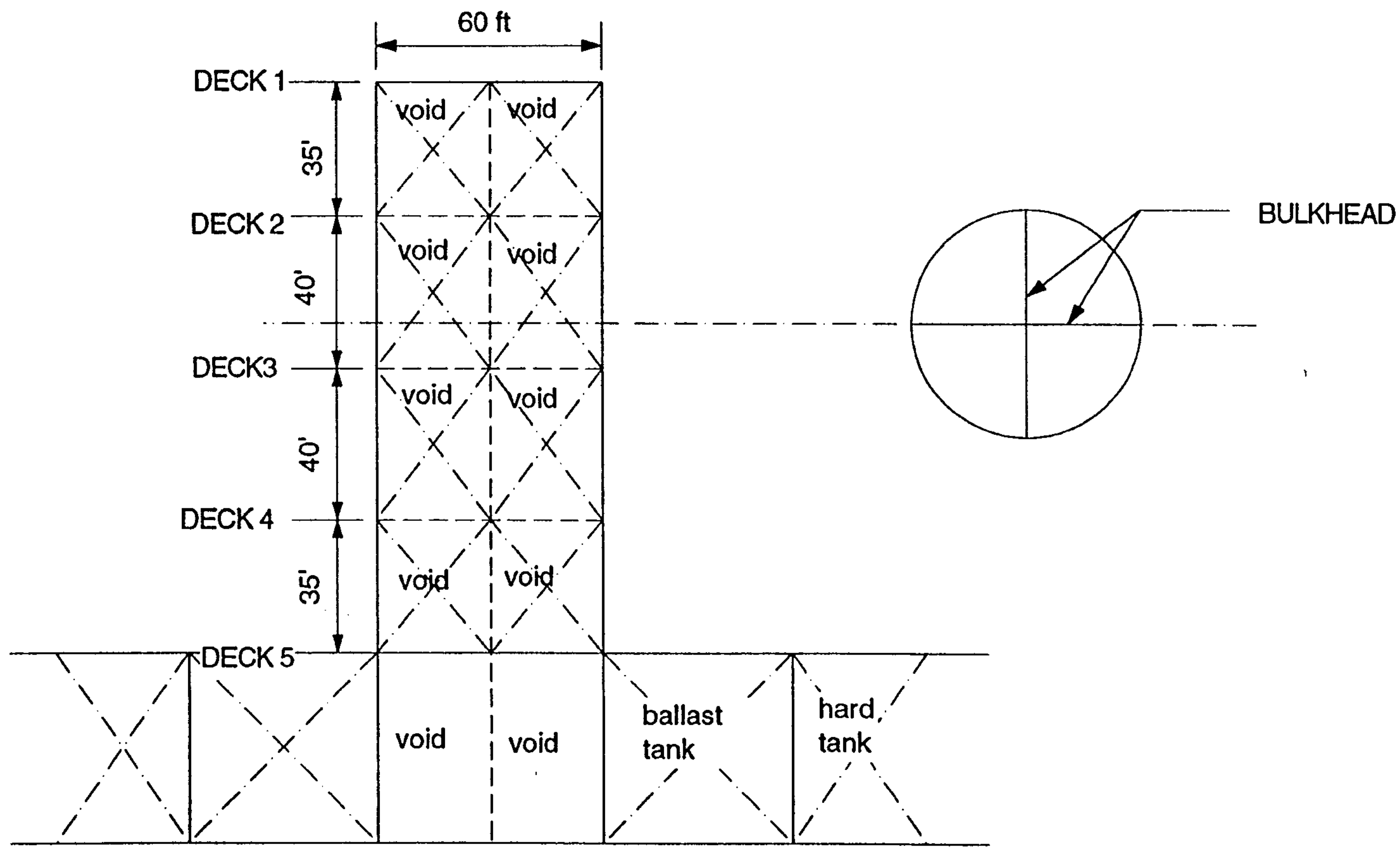


Figure 2.3 Compartmentation of the center column

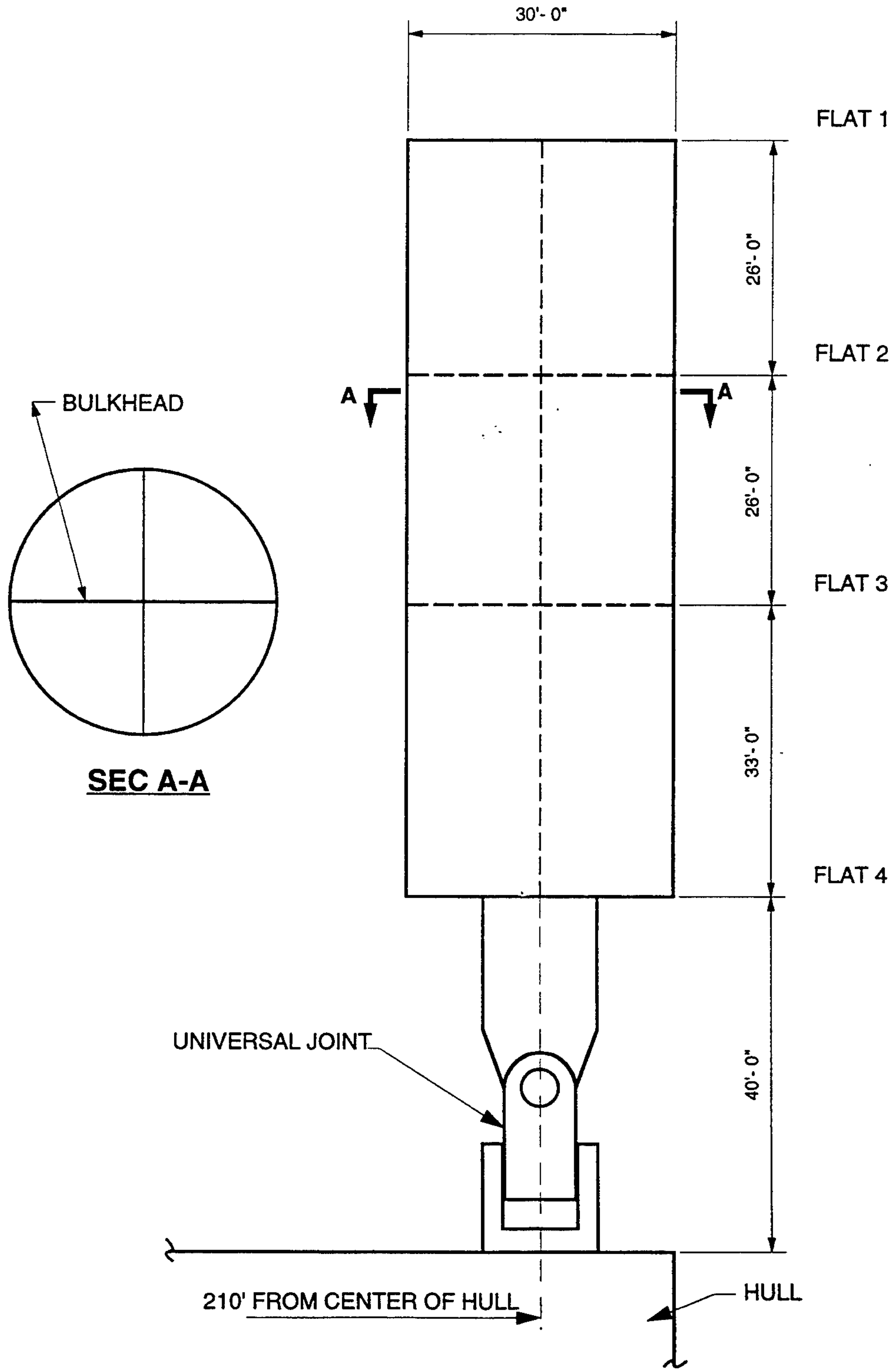


Figure 2.4 Compartmentation of the buoy

CHAPTER 3 HULL SCANTLING AND WEIGHT ESTIMATE

3.1 Structural Scantling

The structural scantlings of the ASOP are based on the Rules for Building and Classing Mobile Offshore Drilling Units and the rules of the American Bureau of Shipping (ABS), Section 5 -- Column-stabilized Drilling Units. The objective of the scantling is to design a preliminary structural arrangement, determine the dimensions of the structural components, and to provide a base for the steel weight estimation. In the scantling, the major structural components, such as shell plate, bulkhead plate, beam, girder, frame and stiffener are determined. Smaller members, such as brackets, stiffeners on the web plate of the girders, and tripping brackets supporting the face plate of the girder, were not designed; however, there are many of those members and their total weight is still significant. The weight of these members is approximated by a percentage of the main structure they attached to. For example, the weight of the stiffeners and tripping brackets on the girder is approximated to be 20 percent of the total weight of the girder. In the scantling, the structural arrangement is not optimized and the size of the members is conservative. Although we considered hydrostatic pressure force as the only external force during the design, the wave induced force is included in an indirect way by using a maximum draft of 165 ft (design draft + 20 ft) for hydrostatic pressure calculations. Figures 3.1 to 3.12 shows the structural arrangement and dimensions of the ASOP hull and buoys. Tables 3.1 to 3.9 show the structural design according to the ABS rules.

3.2 Weight Estimate

The structural weight, outfittings and fixed payload for the ASOP are shown in Table 3.10. The steel weights of the hull and the buoys are based upon the structural scantling. A 20 percent margin is added to the total steel weight of the hull. At this conceptual study stage, the functions of the topside are not totally defined except fuel loading and off-loading, hence the weight of the equipment and payloads on the top side is not definite. Therefore, a total topside weight of 12,000 kips is used in the weight estimation.

3.2.1 Operational

Tabel 3.11 shows the loads at the operational draft of 145 ft. The maximum fuel storage capability is 1 million barrels. As we mentioned earlier, by pumping at a certain ratio simultaneously from the soft tanks and the hard tanks during loading and off-loading, the total weight of fluid in the storage tanks will remain unchanged. The change of variable payload can be easily adjusted by controlling ballast water. The location of the center of gravity (C.G.) and radius of gyration of the platform and buoys are also computed for the stability analysis, motion analysis, and model test (see Chapters 4, 5 and 6).

3.2.2 Transit Draft

During transit there is no fuel stored in the platform. Eight of the twelve small soft tanks will be filled 100 percent with ballast water together with ballast tanks to keep the platform at a draft of 35 ft. The rest of the storage tanks are empty. The buoys are positioned and secured horizontally on the top of the hull and become a fixed load. All the mooring lines and anchors are onboard. Table 3.12 shows the loading conditions for the transit mode.

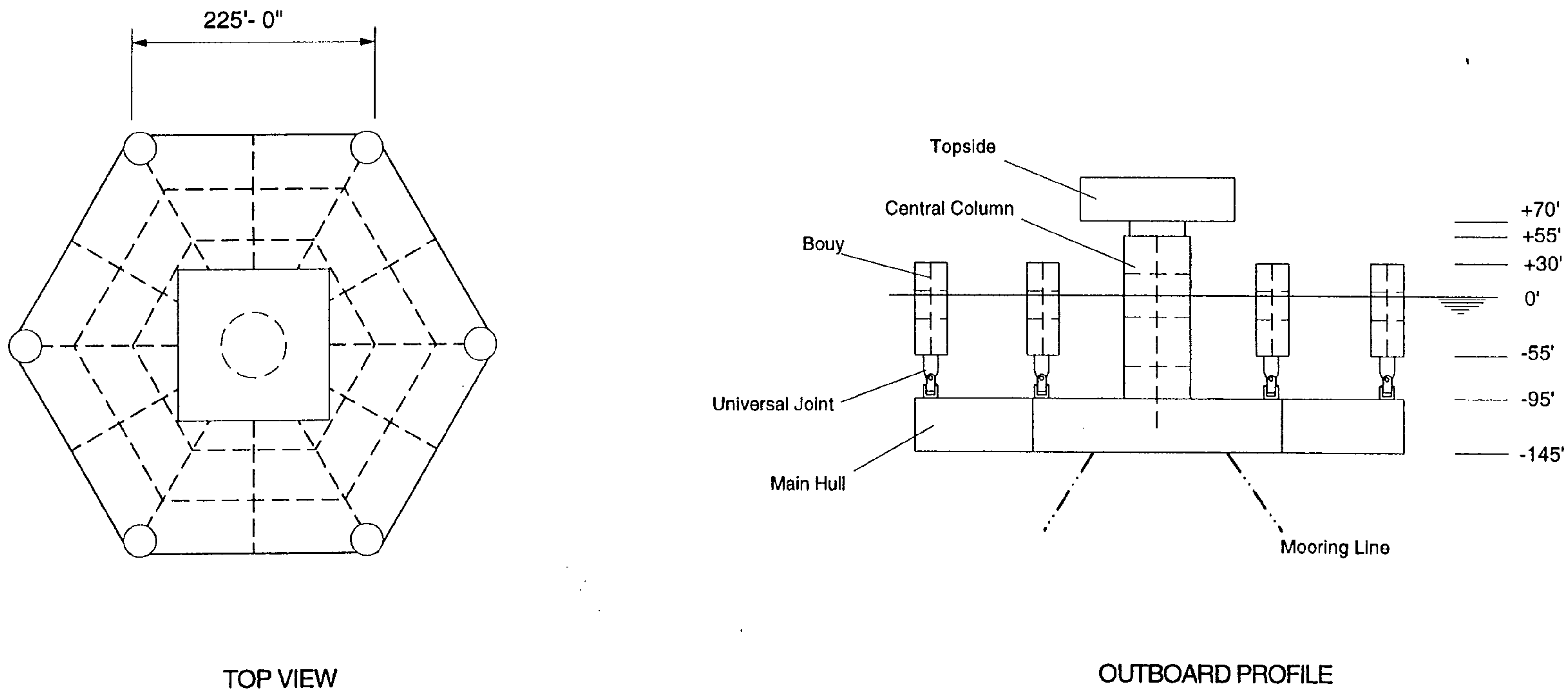


Figure 3.1 General arrangement of the ASOP

	STIFFENER	GIRDER	PLATE THICKNESS
SOFT TANK 1	L8x4x1 3/4	70x3/4x20x1 1/4	3/4"
SOFT TANK 2	L8x4x1 3/4	70x3/4x20x1 1/4	3/4"
HARD TANK	L8x6x1	55x3/4x18x1	1"
BALLAST TANK	L8x6x1	70x3/4x18x1	1"

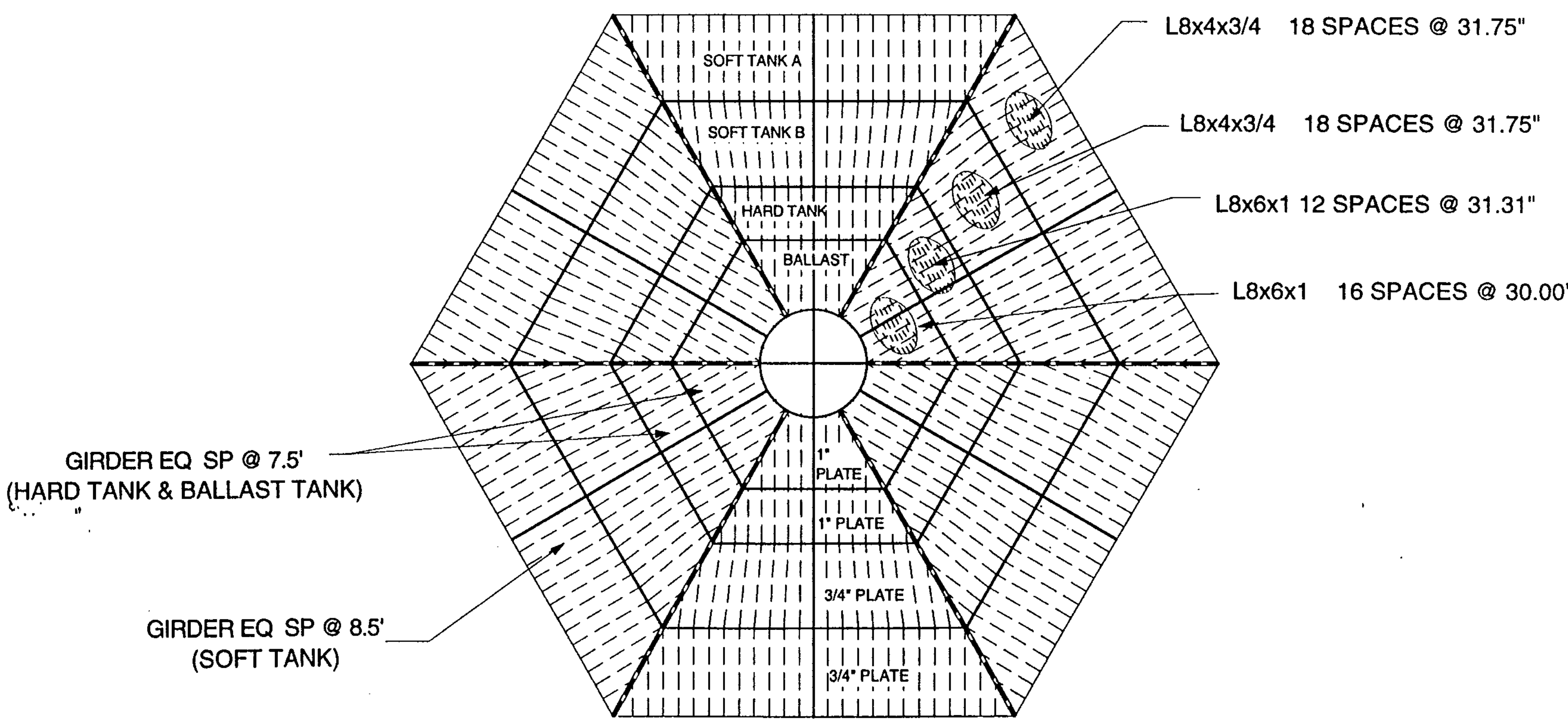


Figure 3.2 The ASOP hull top plate framing

	STIFFENER	GIRDER	PLATE THICKNESS
SOFT TANK 1	L8x4x1 3/4	70x3/4x20x1 1/4	3/4"
SOFT TANK 2	L8x4x1 3/4	70x3/4x20x1 1/4	3/4"
HARD TANK	L9x6x1 1/8	55x3/4x18x1	1"
BALLAST TANK	L9x6x1 1/8	82x1x22x1 3/8	1"

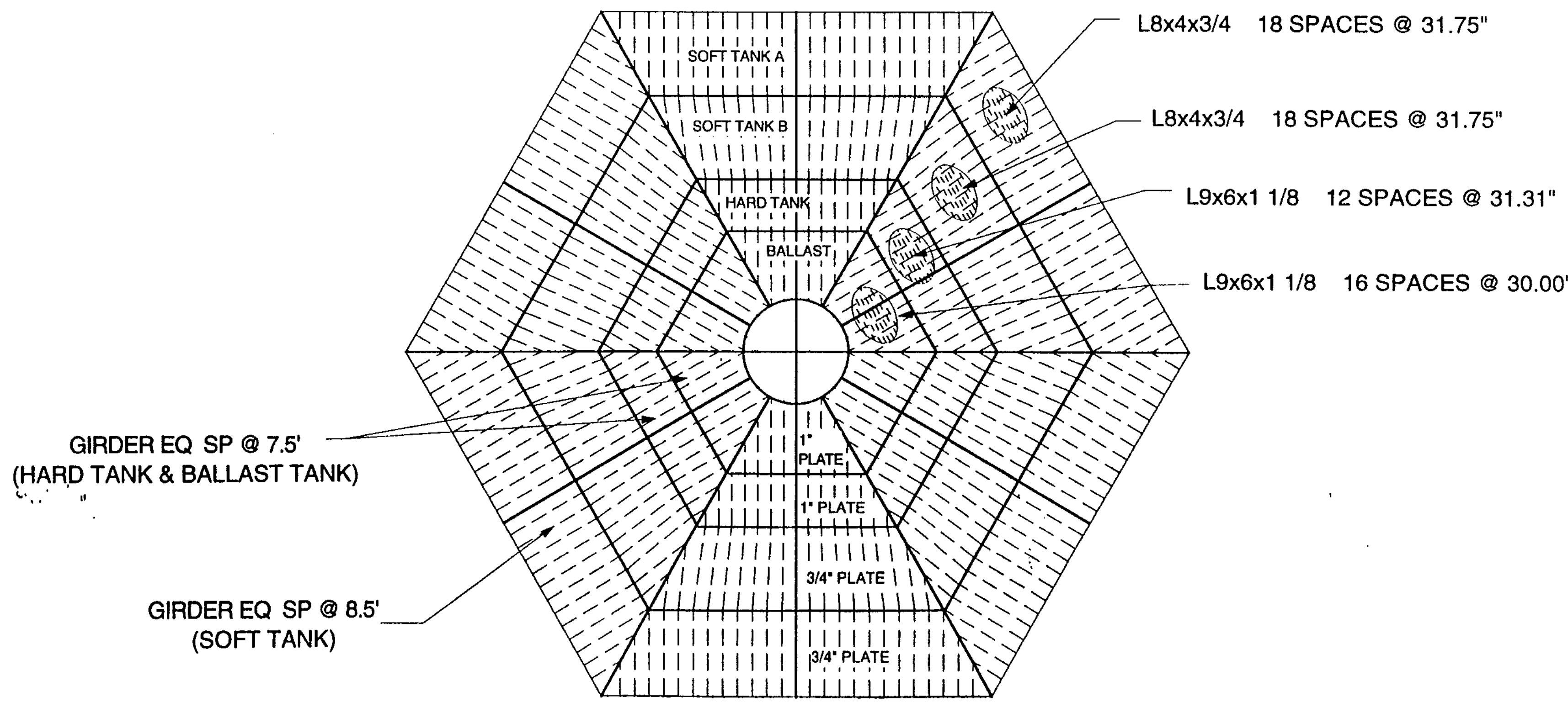


Figure 3.3 The ASOP hull bottom plate framing

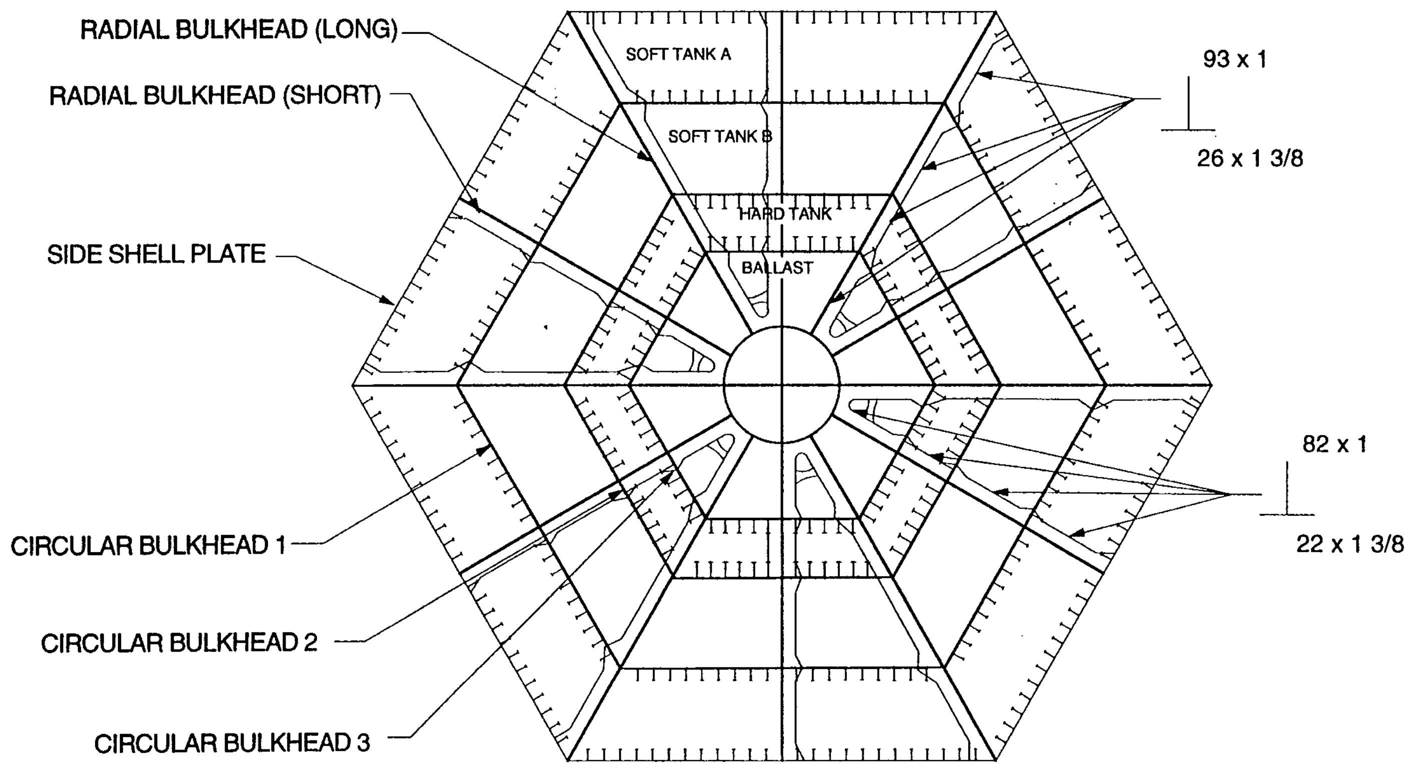


Figure 3.4 The ASOP hull cross section framing

	STIFFENER	GIRDER	PLATE THICKNESS
SOFT TANK 1	L8x6x1 1/8	93x1x26x1 3/8	3/4"
SOFT TANK 2	L8x6x1 1/8	93x1x26x1 3/8	3/4"
HARD TANK	16x1x8x1	93x1x26x1 3/8	1"
BALLAST TANK	16x1x8x1	93x1x26x1 3/8	1"

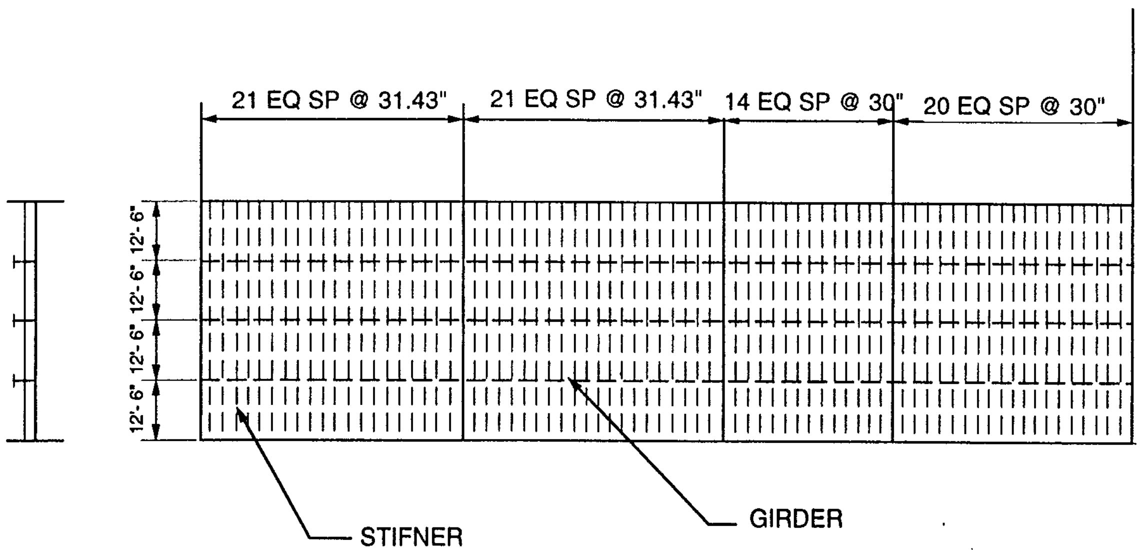


Figure 3.5 The radial bulkhead (long) framing

	STIFFENER	GIRDER	PLATE THICKNESS
SOFT TANK 1	L8x6x1 1/8	82x1x22x1 3/8	3/4"
SOFT TANK 2	L8x6x1 1/8	82x1x22x1 3/8	3/4"
HARD TANK	16x1x8x1	82x1x22x1 3/8	1"
BALLAST TANK	16x1x8x1	82x1x22x1 3/8	1"

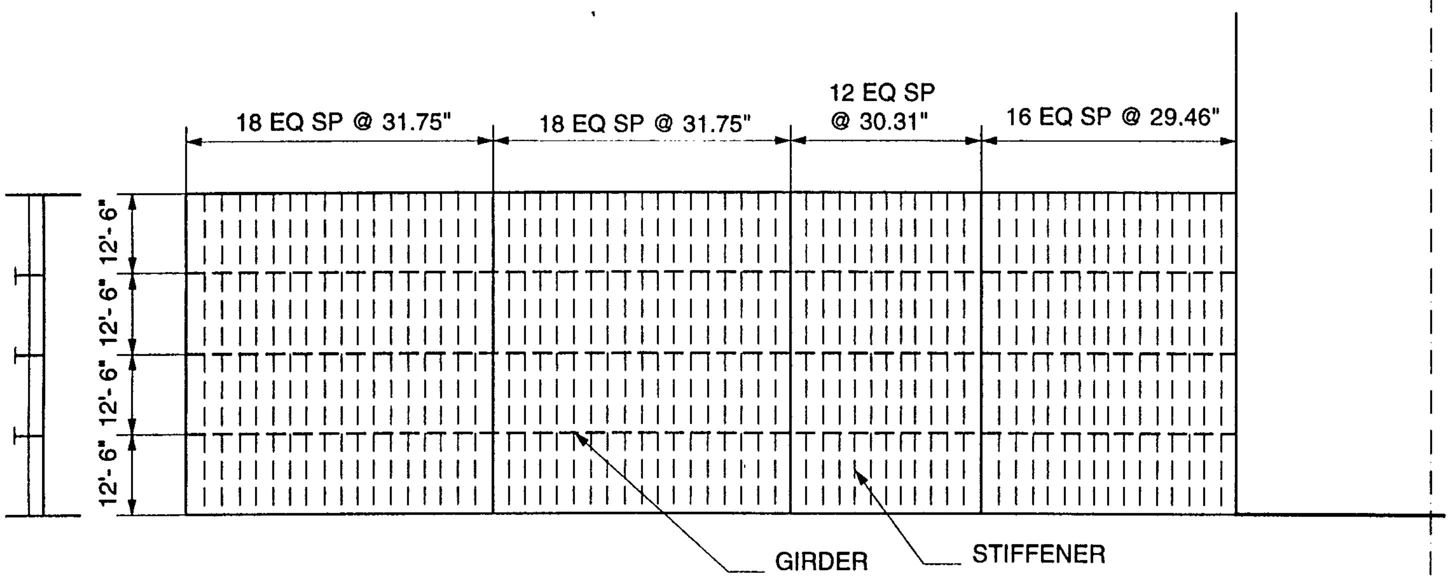


Figure 3.6 The radial bulkhead (short) framing

	STIFFENER	GIRDER	PLATE THICKNESS
SIDE SHELL	L8x4x3/4	70x3/4x20x1 1/4	3/4"
CIRCULAR BULKHEAD 1	L8x4x3/4	70x3/4x20x1 1/4	3/4"
CIRCULAR BULKHEAD 2	L9x6x11/8	93x1x26x1 1/4	1"
CIRCULAR BULKHEAD 3	L9x6x11/8	93x1x26x1 1/4	1"

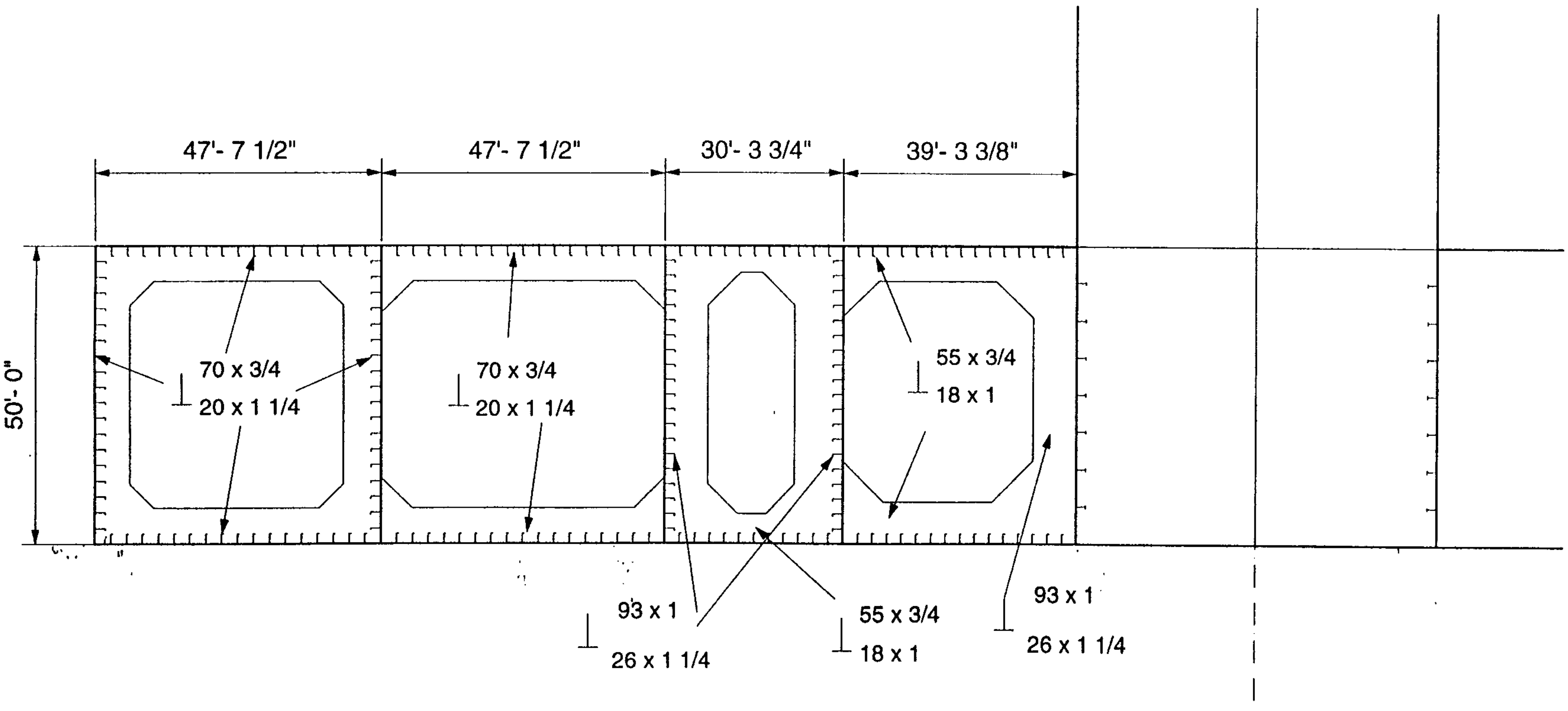
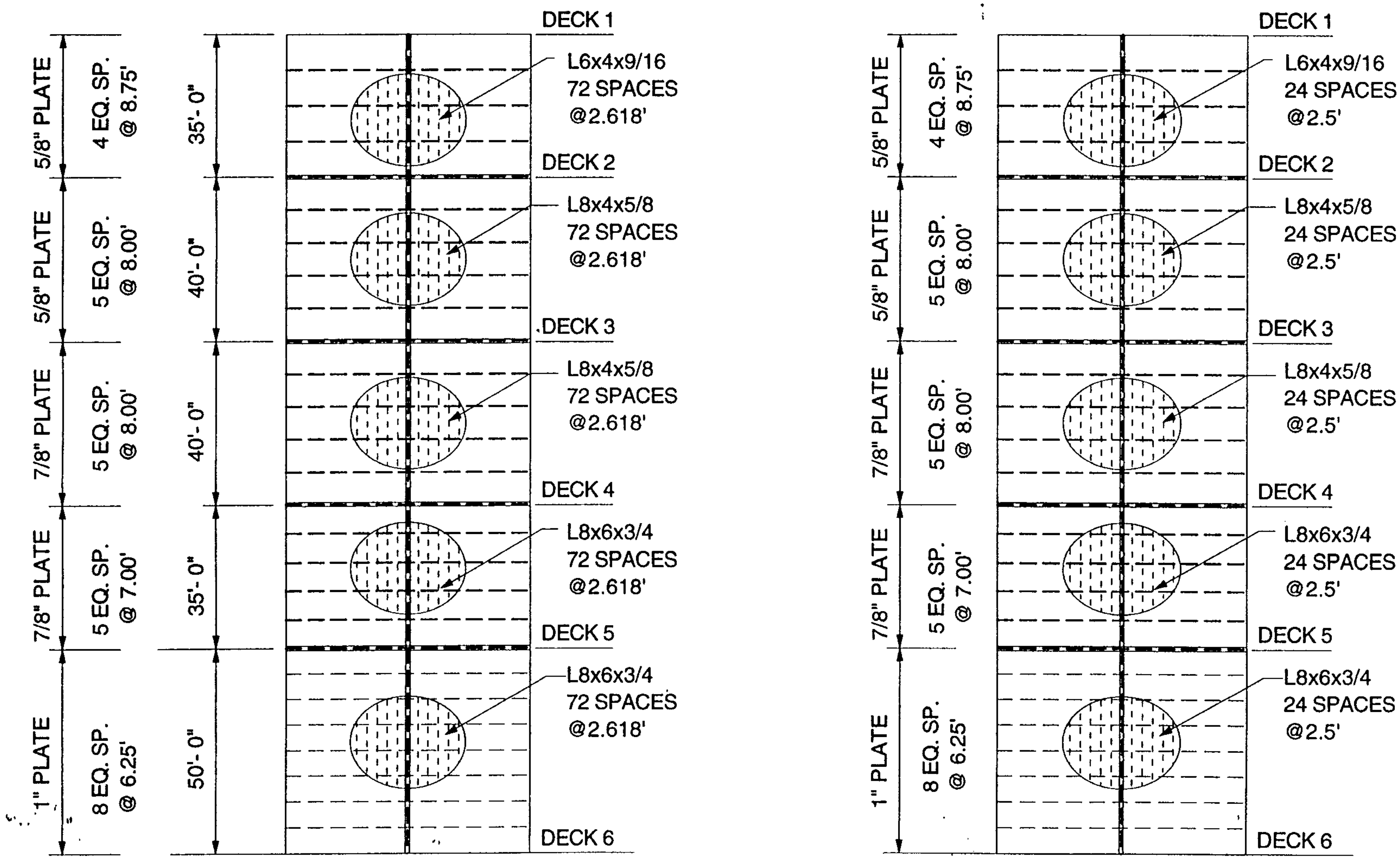


Figure 3.7 The circular bulkheads framing



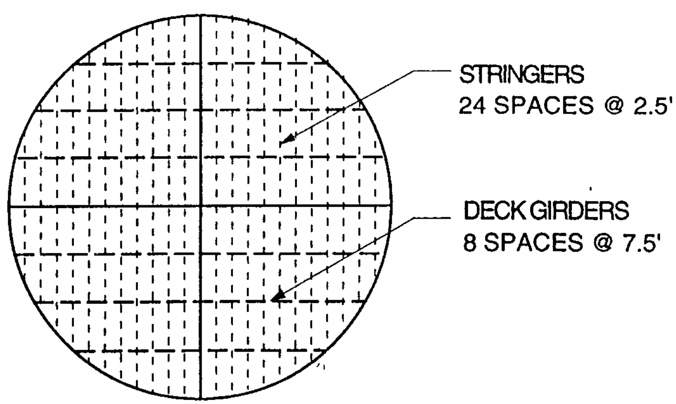
CENTRAL COLUMN OUTER SHELL FRAME

CENTRAL COLUMN BULKHEAD FRAMING

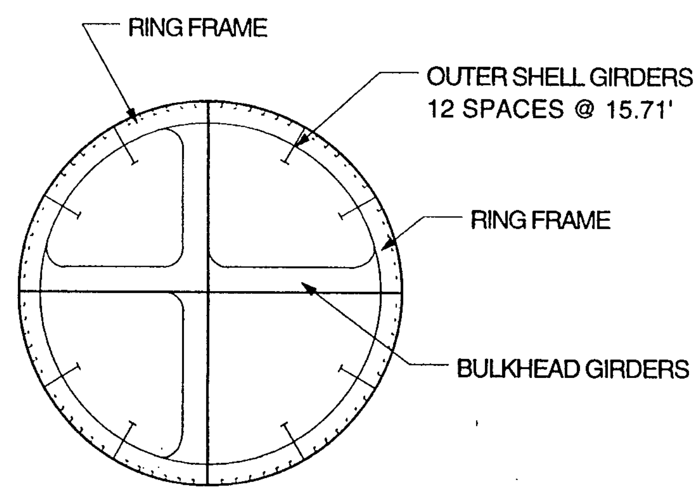
Figure 3.8 The center column outer shell and bulkhead framing

DECK	DECK PLATE	DECK STRINGERS	DECK GIRDER
1	1/2"	L6x4x9/16	45x1/2x10x1
2	1/2"	L6x4x9/16	45x1/2x10x1
3	9/16"	L6x4x9/16	45x1/2x10x1
4	9/16"	L8X4X5/8	50x5/8x14x1
5	9/16"	L8X6X3/4	65x5/8x16x1
6	9/16"	L8X8X7/8	75x5/8x18x1 1/8

BETWEEN DECK	OUTERSHELL GIRDER	RING FRAME	B/H GIRDER
1 & 2	56x1/2x10x3/4	25x1/2x10x1	45x1/2x10x1
2 & 4	75x5/8x15x1	25x1/2x10x1	45x1/2x10x1
3 & 4	75x5/8x15x1	25x1/2x10x1	50x5/8x14x1
4 & 5	85x5/8x20x1	35x1/2x12x1	65x5/8x16x1
5 & 6	-	35x1/2x12x1	75x5/8x18x1 1/8



DECK FRAMING



SECTION- BETWEEN 1&2

Figure 3.9 The center column deck and section framing

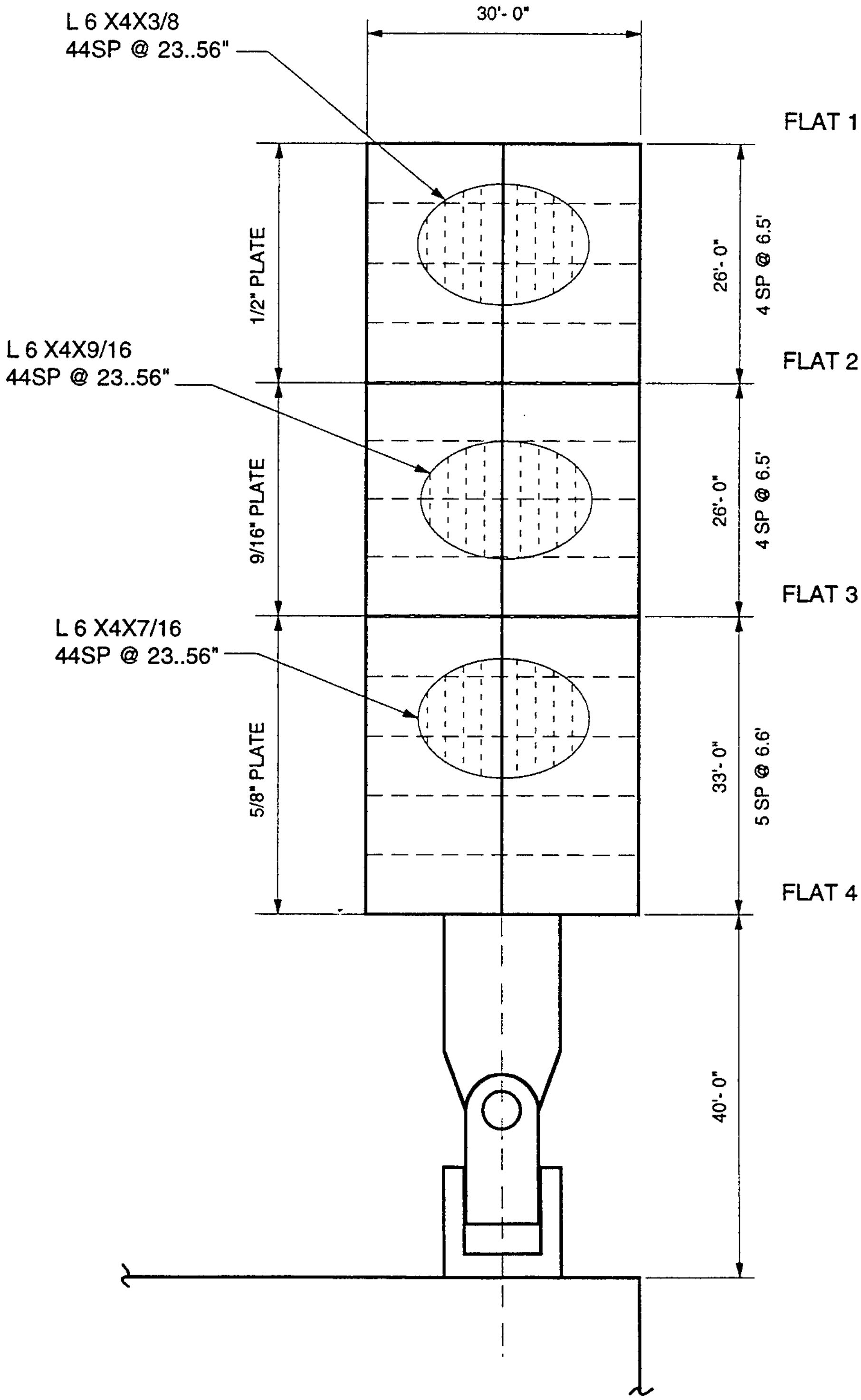


Figure 3.10 The buoy outer shell framing

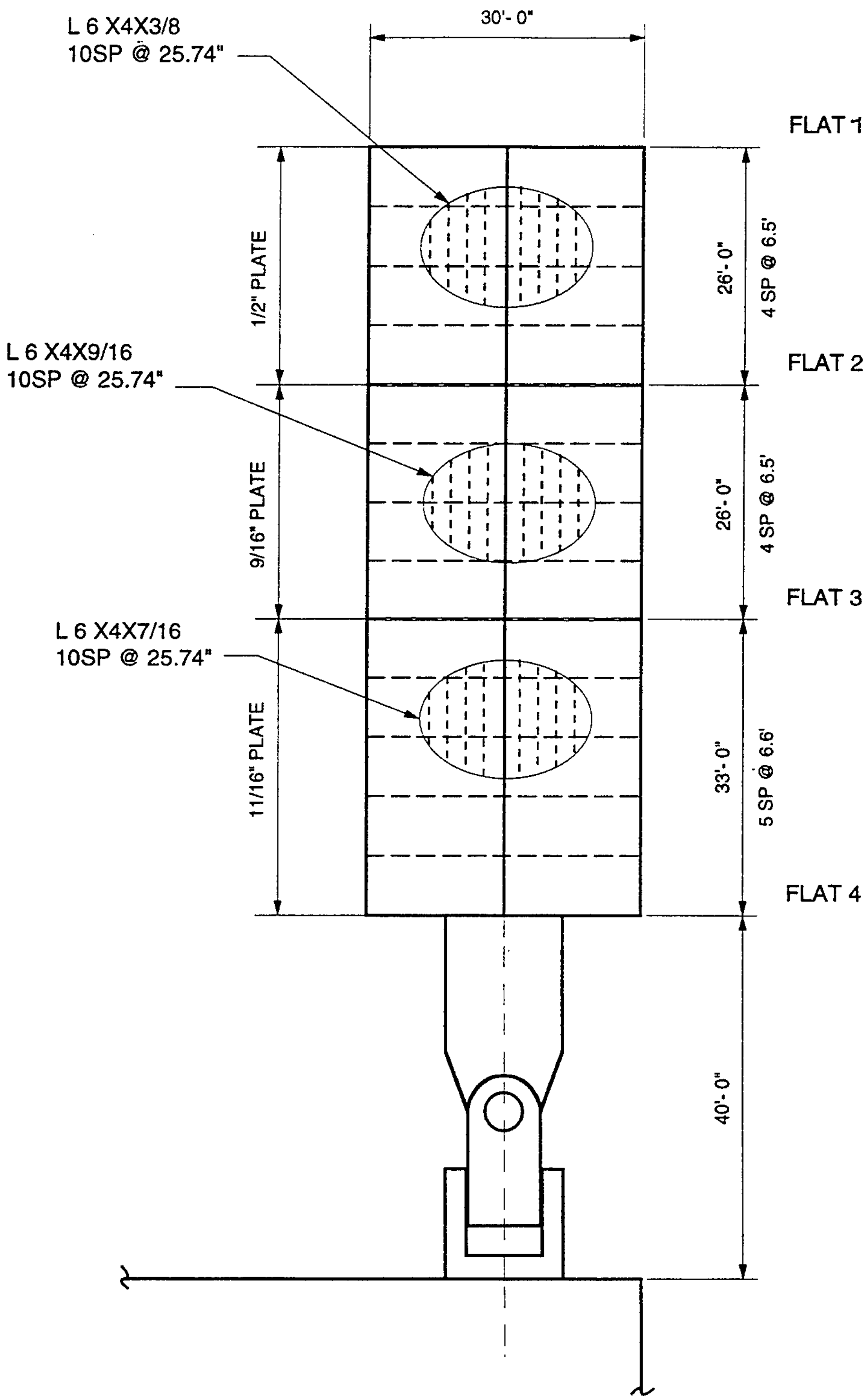
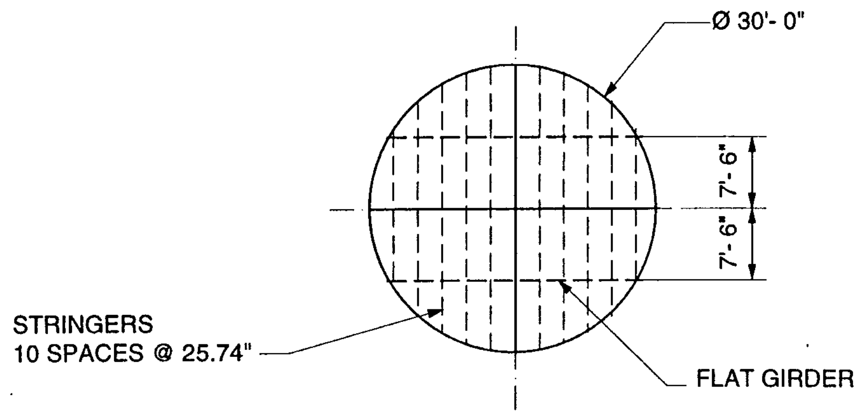


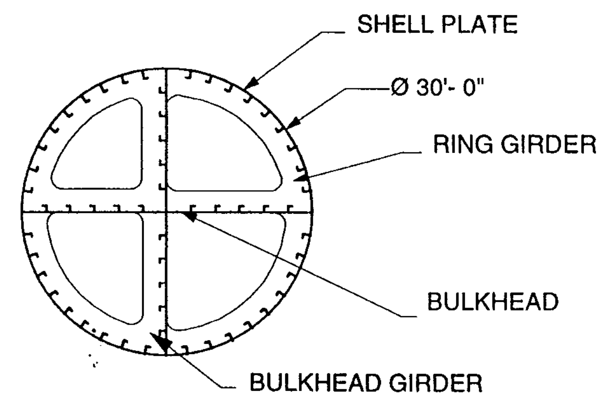
Figure 3.11 The buoy bulkhead framing

FLAT	FLAT PLATE	FLAT STRINGERS	FLAT GIRDER
1	1/2"	L6x4x3/8	23x7/16x10x1/2
2	1/2"	L6x4x3/8	23x7/16x10x1/2
3	9/16"	L8x4x7/16	23x7/16x10x3/4
4	9/16"	L8X6X9/16	25x1/2x12x1

BETWEEN FLAT	RING GIRDER	B/H GIRDER
1 & 2	36x7/16x10x1/2	23x7/16x10x1/2
2 & 4	36x1/2x12x1	23x7/16x10x3/4
3 & 4	40x1/2x17x1	25x1/2x12x1



FLAT FRAMING



SECTION - BETWEEN FLAT 1 & 2

Figure 3.12 The buoy flat and section framing

Table 3.1 The buoy outer shell and bulkhead plating

PLATE LOCATION	STIFFENER SPACING (IN)	FRAME SPACING (FT)	HEAD (FT)	ABS THICKNESS (IN)	ACTUAL THICKNESS (IN)	
OUTER SHELL PL						
COMPARTMENT 1	23.56	6.5380	30.00	0.381	0.5000	O.K.
COMPARTMENT 2	23.56	6.5380	63.00	0.507	0.5625	O.K.
COMPARTMENT 3	23.56	6.5380	95.00	0.599	0.6250	O.K.
BULKHEAD						
COMPARTMENT 1	25.74	6.5380	30.00	0.406	0.5000	O.K.
COMPARTMENT 2	25.74	6.5380	63.00	0.544	0.5625	O.K.
COMPARTMENT 3	25.74	6.5380	95.00	0.645	0.6875	O.K.
HORI. FLAT						
FLAT 1	25.74	7.5000	30.00	0.406	0.5000	O.K.
FLAT 2	25.74	7.5000	30.00	0.406	0.5000	O.K.
FLAT 3	25.74	7.5000	63.00	0.544	0.5625	O.K.
FLAT 4	25.74	7.5000	95.00	0.645	0.6875	O.K.

Table 3.2 The buoy frame structural (girder) scantling

LOCATION	C	H	S	L	Q	ABS REQ'D.	ACTUAL	ACTUAL SIZE	RECOMMEND
		(FT)	(FT)	(FT)		SM	SM		
OUT SHELL									
COMPARTMENT 1	1.50	24.00	6.538	23.562	0.720	235.20	343.31	36 X 7/16 X 10 X 1/2	O.K.
COMPARTMENT 2	1.50	57.00	6.538	23.562	0.720	558.61	582.33	36 X1/2 X 12 X 1	O.K.
COMPARTMENT 3	1.50	89.00	6.538	23.562	0.720	872.21	882.42	40 X 3/4 X 17 X 1	O.K.
BULKHEAD									
COMPARTMENT 1	1.50	24.00	6.538	15.000	0.720	95.32	179.98	23 X 7/16 X 10 X 1/2	O.K.
COMPARTMENT 2	1.50	57.00	6.538	15.000	0.720	226.39	235.31	23 X 7/16 X 10 X 3/4	O.K.
COMPARTMENT 3	1.50	89.00	6.538	15.000	0.720	353.49	380.59	25 X 1/2 X 12 X 1	O.K.
HORI. FLAT									
FLAT 1	1.50	30.00	7.500	12.990	0.720	102.51	179.98	23 X 7/16 X 10 X 1/2	O.K.
FLAT 2	1.50	30.00	7.500	12.990	0.720	102.51	179.98	23 X 7/16 X 10 X 1/2	O.K.
FLAT 3	1.50	63.00	7.500	12.990	0.720	215.27	235.31	23 X 7/16 X 10 X 3/4	O.K.
FLAT 4	1.50	95.00	7.500	12.990	0.720	324.61	380.59	25 X 1/2 X 12 X 1	O.K.

Table 3.3 The buoy frame structural (stiffener) scantling

STIFF	C	H	S	L	Q	ABS REQ'D.	ACTUAL	ACTUAL SIZE	RECOMMEND
LOCATION		(FT)	(FT)	(FT)		SM	SM		
OUTER SHELL									
COMPARTMENT 1	1.00	27.00	1.963	6.538	0.720	6.69	12.41	L6 X4 X 3/8	O.K.
COMPARTMENT 2	1.00	60.00	1.963	6.538	0.720	14.86	17.63	L6 x 4 x 9/16	O.K.
COMPARTMENT 3	1.00	92.00	1.963	6.538	0.720	22.79	28.31	L8 x 4 x 7/16	O.K.
BULKHEAD									
COMPARTMENT 1	1.00	27.00	2.145	6.538	0.720	7.31	12.41	L6 X4 X 3/8	O.K.
COMPARTMENT 2	1.00	60.00	2.145	6.538	0.720	16.24	17.63	L6 x 4 x 9/16	O.K.
COMPARTMENT 3	1.00	92.00	2.145	6.538	0.720	24.90	28.31	L8 x 4 x 7/16	O.K.
HORI. FLAT									
FLAT1	1.00	30.00	2.145	7.500	0.720	10.69	12.41	L6 X4 X 3/8	O.K.
FLAT2	1.00	30.00	2.145	7.500	0.720	10.69	12.41	L6 X4 X 3/8	O.K.
FLAT3	1.00	63.00	2.145	7.500	0.720	22.44	28.31	L8 x 4 x 7/16	O.K.
FLAT4	1.00	95.00	2.145	7.500	0.720	33.84	34.29	L8 x 6 x 9/16	O.K.

Table 3.4 The hull outer shell and bulkhead plating

PLATE LOCATION	STIFFENER SPACING (IN)	FRAME SPACING (FT)	HEAD (FT)	ABS THICKNESS (IN)	ACTUAL THICKNESS (IN)	
SOFT TANK						
SIDE HELL	31.75	8.5000	53.00	0.602	0.750	O.K.
TOP PLATE	31.75	8.5000	53.00	0.603	0.750	O.K.
BOTTON PLATE	31.75	8.5000	53.00	0.602	0.750	O.K.
RADIAL BULKHEAD	31.75	12.5000	53.00	0.602	0.750	O.K.
HARD TANK						
SIDE HELL	30.31	7.5000	165.00	0.946	1.000	O.K.
TOP PLATE	30.31	7.5000	115.00	0.807	1.000	O.K.
BOTTON PLATE	30.31	7.5000	165.00	0.946	1.000	O.K.
RADIAL BULKHEAD	30.31	12.5000	165.00	0.946	1.000	O.K.
BALLAST TANK						
SIDE HELL	30.00	7.5000	165.00	0.938	1.000	O.K.
TOP PLATE	30.00	7.5000	115.00	0.799	1.000	O.K.
BOTTON PLATE	30.00	7.5000	165.00	0.938	1.000	O.K.
RADIAL BULKHEAD	30.00	12.5000	165.00	0.938	1.000	O.K.

Table 3.5 The hull Frame structural (girder) scantling

LOCATION	C	H	S	L	Q	ABS REQ'D.	ACTUAL	ACTUAL SIZE	RECOMMEND
		(FT)	(FT)	(FT)		SM	SM		
SOFT TANK 1									
SIDE	1.50	53.00	8.50	38.330	0.720	1787.05	2654.00	70 X 1 X 20 X 1 1/4	O.K.
TOP	1.50	53.00	8.50	37.000	0.720	1665.18	2654.00	70 X 1 X 20 X 1 1/4	O.K.
BOTTOM	1.50	53.00	8.50	37.000	0.720	1665.18	2654.00	70 X 1 X 20 X 1 1/4	O.K.
SOFT TANK 2									
TOP	1.50	53.00	8.50	45.630	0.720	2532.56	2654.00	70 X 1 X 20 X 1 1/4	O.K.
BOTTOM	1.50	53.00	8.50	45.630	0.720	2532.56	2654.00	70 X 1 X 20 X 1 1/4	O.K.
HARD TANK									
SIDE	1.50	165.00	7.50	39.580	0.720	5234.32	5309.08	93 X 1 X 26 X 1 3/8	O.K.
TOP	1.50	115.00	7.50	15.000	0.720	523.97	1615.14	55 X 3/4 X 18 X 1	O.K.
BOTTOM	1.50	165.00	7.50	15.000	0.720	751.78	1615.14	55 X 3/4 X 18 X 1	O.K.
BALLAST TANK									
SIDE	1.50	165.00	7.50	37.330	0.720	4656.13	5309.08	93 X 1 1/8 X 26 X 1 3/8	O.K.
TOP	1.50	115.00	7.50	33.550	0.720	2621.25	2654.00	70 X 1 X 20 X 1 1/4	O.K.
BOTTOM	1.50	165.00	7.50	33.550	0.720	3760.92	4088.66	82 X 1 X 22 X 1 3/8	O.K.
RADIAL BULKHEAD 1									
SOFT TANK	1.50	53.00	12.50	44.630	0.720	3562.90	4088.66	82 X 1 X 22 X 1 3/8	O.K.
HARD TANK	1.50	152.50	12.50	27.300	0.720	3835.91	4088.66	82 X 1 X 22 X 1 3/8	O.K.
BALLAST TANK	1.50	152.50	12.50	36.800	0.720	6970.10	4088.66	82 X 1 X 22 X 1 3/8	O.K. (WITH STRUT)
RADIAL BULKHEAD 2									
SOFT TANK	1.50	53.00	12.50	52.000	0.720	4836.78	5309.08	93 X 1 1/8 X 26 X 1 3/8	O.K.
HARD TANK	1.50	152.50	12.50	32.000	0.720	5270.40	5309.08	93 X 1 1/8 X 26 X 1 3/8	O.K.
BALLAST TANK	1.50	152.50	12.50	42.500	0.720	9296.54	5309.08	93 X 1 1/8 X 26 X 1 3/8	O.K. (WITH STRUT)

Table 3.6 The hull Frame structural (stiffener) scantling

STIFF LOCATION	C	H (FT)	S (FT)	L (FT)	Q	ABS REQ'D. SM	ACTUAL SM	ACTUAL SIZE	RECOMMEND
SHELL & CIRCULAR BULKHEAD									
SOFT TANK	1.00	52.00	2.646	8.500	0.720	29.35	34.38	L8 X4 X 3/4	O.K.
HARD TANK	1.00	165.00	2.526	7.500	0.720	69.21	75.90	L9 x 6 x 1 1/8	O.K.
BALLAST TANK	1.00	165.00	2.500	7.500	0.720	68.50	75.90	L9 x 6 x 1 1/8	O.K.
RADIAL BULKHEAD									
SOFT TANK	1.00	52.00	2.646	12.500	0.720	63.46	63.55	L8 x 6 x 1 1/8	O.K.
HARD TANK	1.00	165.00	2.526	12.500	0.720	192.24	195.97	16 X 1 X 8 X 1	O.K.
BALLAST TANK	1.00	165.00	2.500	12.500	0.720	190.27	195.97	16 X 1 X 8 X 1	O.K.
TOP PLATE									
SOFT TANK	1.00	53.00	2.646	8.500	0.720	29.91	34.38	L8 X4 X 3/4	O.K.
HARD TANK	1.00	115.00	2.526	7.500	0.720	48.24	58.41	L8 X6 X 1	O.K.
BALLAST TANK	1.00	115.00	2.500	7.500	0.720	47.74	58.41	L8 X6 X 1	O.K.
BOTTOM PLATE									
SOFT TANK	1.00	53.00	2.646	8.500	0.720	29.91	34.38	L8 X4 X 3/4	O.K.
HARD TANK	1.00	165.00	2.526	7.500	0.720	69.21	75.90	L9 x 6 x 1 1/8	O.K.
BALLAST TANK	1.00	165.00	2.500	7.500	0.720	68.50	75.90	L9 x 6 x 1 1/8	O.K.

Table 3.7 The center column outer shell and bulkhead plating

PLATE LOCATION	STIFFENER SPACING (IN)	FRAME SPACING (FT)	HEAD (FT)	ABS THICKNESS (IN)	ACTUAL THICKNESS (IN)	
OUTER SHELL PL						
COMPARTMENT 1	31.415	8.7500	35.00	0.504	0.625	O.K.
COMPARTMENT 2	31.415	8.0000	40.00	0.532	0.625	O.K.
COMPARTMENT 3	31.415	8.0000	80.00	0.711	0.875	O.K.
COMPARTMENT 4	31.415	7.0000	115.00	0.832	0.875	O.K.
COMPARTMENT 5	31.415	6.2500	165.00	0.977	1.000	O.K.
BULKHEAD						
COMPARTMENT 1	30.000	8.7500	35.00	0.486	0.625	O.K.
COMPARTMENT 2	30.000	8.0000	40.00	0.512	0.625	O.K.
COMPARTMENT 3	30.000	8.0000	80.00	0.683	0.875	O.K.
COMPARTMENT 4	30.000	7.5000	115.00	0.799	0.875	O.K.
COMPARTMENT 5	30.000	6.2500	165.00	0.938	1.000	O.K.
DECK						
DECK1	30.000	7.5000	35.00	0.486	0.500	O.K.
DECK2	30.000	7.5000	35.00	0.486	0.500	O.K.
DECK3	30.000	7.5000	40.00	0.512	0.625	O.K.
DECK4	30.000	7.5000	80.00	0.683	0.875	O.K.
DECK5	30.000	7.5000	115.00	0.799	0.875	O.K.
DECK6	30.000	7.5000	165.00	0.938	1.000	O.K.

Table 3.8 The center column frame structural (girder) scantling

LOCATION	C	H	S	L	Q	ABS REQ'D.	ACTUAL	ACTUAL SIZE	RECOMMEND
		(FT)	(FT)	(FT)		SM	SM		
OUT SHELL									
LONG. GIRDER									
COMPARTMENT 1	1.50	20.00	15.710	32.000	0.720	868.70	1109.60	65 X 7/8 X 10 X 3/4	O.K.
COMPARTMENT 2	1.50	40.00	15.710	37.000	0.720	2322.75	2605.52	75 X 1 X 15 X 1	O.K.
COMPARTMENT 3	1.50	65.00	15.710	37.000	0.720	3774.48	3852.61	85 X 1 X 20 X 1 1/8	O.K.
COMPARTMENT 4	1.50	100.00	15.710	32.000	0.720	4343.50	4529.69	90 X 1 1/8 X 22 X 1 1/4	O.K.
RING FRAME									
COMPARTMENT 1	1.50	27.00	8.750	15.710	0.720	157.43	334.46	25 X 1/2 X 10 X 1	O.K.
COMPARTMENT 2	1.50	32.00	8.000	15.710	0.720	170.59	334.46	25 X 1/2 X 10 X 1	O.K.
COMPARTMENT 3	1.50	72.00	8.000	15.710	0.720	383.83	334.46	25 X 1/2 X 10 X 1	O.K.
COMPARTMENT 4	1.50	108.00	7.000	15.710	0.720	503.78	591.92	35 X 1/2 X 12 X 1	O.K.
COMPARTMENT 5	1.50	158.75	6.250	15.710	0.720	661.17	731.31	45 X 1/2 X 10 X 1	O.K.
BULKHEAD									
COMPARTMENT 1	1.50	27.00	8.750	30.000	0.720	574.09	731.31	45 X 1/2 X 10 X 1	O.K.
COMPARTMENT 2	1.50	32.00	8.000	30.000	0.720	622.08	731.31	45 X 1/2 X 10 X 1	O.K.
COMPARTMENT 3	1.50	72.00	8.000	30.000	0.720	1399.68	1702.52	65 X 7/8 X 16 X 1	O.K.
COMPARTMENT 4	1.50	108.00	7.000	30.000	0.720	1837.08	2433.41	75 X 1 X 18 X 1 1/8	O.K.
COMPARTMENT 5	1.50	158.75	6.250	30.000	0.720	2411.02	2433.41	75 X 1 X 18 X 1 1/8	O.K.
DECK									
DECK1	1.50	35.00	7.500	29.000	0.720	596.06	731.31	45 X 1/2 X 10 X 1	O.K.
DECK2	1.50	35.00	7.500	29.000	0.720	596.06	731.31	45 X 1/2 X 10 X 1	O.K.
DECK3	1.50	45.00	7.500	29.000	0.720	766.36	1702.52	65 X 7/8 X 16 X 1	O.K.
DECK4	1.50	85.00	7.500	29.000	0.720	1447.57	1702.52	65 X 7/8 X 16 X 1	O.K.
DECK5	1.50	115.00	7.500	29.000	0.720	1958.48	2433.41	75 X 1 X 18 X 1 1/8	O.K.
DECK6	1.50	165.00	7.500	29.000	0.720	2809.99	3074.34	85 X 1 X 20 X 1	O.K.

Table 3.9 The center column frame structural (stiffener) scantling

STIFF	C	H	S	L	Q	ABS REQ'D.	ACTUAL	ACTUAL SIZE	RECOMMEND
LOCATION		(FT)	(FT)	(FT)		SM	SM		
OUTER SHELL									
COMPARTMENT 1	1.00	35.00	2.618	8.750	0.720	20.71	29.04	L8 x 4 x 5/8	O.K.
COMPARTMENT 2	1.00	45.00	2.618	8.000	0.720	22.26	46.09	L8 x 6 x 3/4	O.K.
COMPARTMENT 3	1.00	85.00	2.618	8.000	0.720	42.04	46.09	L8 x 6 x 3/4	O.K.
COMPARTMENT 4	1.00	115.00	2.618	7.000	0.720	43.55	53.49	L9 x 6 x 3/4	O.K.
COMPARTMENT 5	1.00	165.00	2.618	6.250	0.720	49.81	53.13	L9 x 6 x 3/4	O.K.
BULKHEAD									
COMPARTMENT 1	1.00	35.00	2.500	8.750	0.720	19.78	29.04	L8 x 4 x 5/8	O.K.
COMPARTMENT 2	1.00	45.00	2.500	8.000	0.720	21.25	46.09	L8 x 6 x 3/4	O.K.
COMPARTMENT 3	1.00	85.00	2.500	8.000	0.720	40.15	46.09	L8 x 6 x 3/4	O.K.
COMPARTMENT 4	1.00	115.00	2.500	7.000	0.720	41.59	53.49	L9 x 6 x 3/4	O.K.
COMPARTMENT 5	1.00	165.00	2.500	6.250	0.720	47.57	53.13	L9 x 6 x 3/4	O.K.
DECK									
DECK1	1.00	35.00	2.500	7.500	0.720	14.53	17.99	L6 X4 X 9/16	O.K.
DECK2	1.00	35.00	2.500	7.500	0.720	14.53	17.99	L6 X4 X 9/16	O.K.
DECK3	1.00	45.00	2.500	7.500	0.720	18.68	29.04	L8 x 4 x 5/8	O.K.
DECK4	1.00	85.00	2.500	7.500	0.720	35.29	45.98	L8 x 6 x 3/4	O.K.
DECK5	1.00	115.00	2.500	7.500	0.720	47.74	53.69	L9 x 6 x 3/4	O.K.
DECK6	1.00	165.00	2.500	7.500	0.720	68.50	71.80	L9 x 8 x 7/8	O.K.

Table 3.10 Structural and fixed equipment weight

Item		Weight (kips)
Topside		
	Total weight	12,000
Hull		
	Structural steel	72,711
	Fixed ballast	4,204
	Piping system	1,000
	Mooring winches and equipment	800
	Universal joints (6)	900
	Hull fittings and anodes	1,000
	Ladders	500
	Total weight	81,115
Buoys (6)		
	Structural steel	4,620
	Outfitting	480
	Total weight	5,100
Total weight without buoys		93,115
Total weight with buoys		98,215

Table 3.11 Weight list at operational draft (145 ft)

ASOP without buoys	
Structural and fixed weight (without buoys)	93,115 kips
Fuel Storage	306,300 kips
Variable payload	3,000 kipe
Water ballast	44,000 kips
Total weight	446,415 kips
C.G.	33 ft (above keel)
Radius of gyration	
Roll	109 ft
Pitch	109 ft
Yaw	142 ft
Buoy	
Total weight	850 kips each
C.G.	43 ft (above bottom plate)
Radius of gyration	
Roll	26
Pitch	26
Yaw	13
Total weight of ASOP	451,515 kips
Vertical mooring load	1,350 kips
Total displacement	452,865 kips

Table 3.12 Weight list at transit draft (35 ft)

Structural and fixed weight	98,215 kips
Fuel Storage	0 kips
Mooring lines and anchors	3,000 kips
Variable payload	1,000 kips
Water ballast in 8 soft tanks	172,760 kips
Water ballast in ballast tanks	19,647 kips
Total weight	294,622 kips
C.G.	38 ft (above keel)
Total displacement	294,622 kips

CHAPTER 4 STABILITY

4.1 General

The stability of the ASOP is mainly provided by the six articulated buoys located at each corner of the hexagonal hull. The center column has little contribution for intact stability but provides much needed reserved buoyancy in the damaged condition. The superstructure (topside) is not designed to provide buoyancy for the platform. Although the water plane area is small compared to other types of column stabilized platforms, the large spacing between the buoys gives a considerable amount of restoring force when the platform is heeling (The restoring moment is proportional to the square of spacing between buoys across the corners). On the other hand, the articulation of the buoys raises a unique problem for the stability of the platform which does not exist in fixed column platforms such as semi-submersibles. At certain heeling angles, the buoys at one side rise to a draft where the buoy can not stay upright anymore. In this condition, the buoy will assume a stable equilibrium position that is inclined at a certain heel angle to the vertical and will dramatically lose its contribution to the stability. This can be explained by looking at the vertical force on the universal joints. Figure 4.1 shows the vertical force at the universal joint as a function of the vertical position of the joint. The slope of the curve shows how effectively the buoy contributes to stability. A steeper slope of the curve means a large restoring moment will be created for the same heeling angle. When the vertical distance between the joint and the water line is less than 55 ft and the buoy can not stay vertically anymore, the slope of the curve is reduced dramatically and the buoy is no longer effective to the stability. In addition, once the buoy is totally submerged in the water, it will not provide further restoring force when the platform continues to heel. Also the relative movement of the center of buoyancy of the buoys to the hull during heel reduces the restoring moment. These unique characteristics of the articulated buoy will raise problems for large angle stability of the ASOP. In the following two sections, the intact and damaged stability of the ASOP will be discussed.

4.2 Intact Stability

4.2.1 Stability Criteria

The stability criteria used in the ASOP design is the US Coast Guard rules for mobile offshore drilling units (Code of Federal Regulations, Title 46 -- Shipping, Chapter I, Part 174, Subpart C). The American Bureau of Shipping has very similar rules for mobile offshore drilling units. The major requirements in these rules are:

1) The area under the righting moment curve from the angle of 0 to the second intercept of the righting and wind overturning moment curves or the downflood angle, whichever is less, shall be more than 1.3 times greater than the area under the wind overturning moment curve to the same limiting angle.

2) The righting moment must be positive for all angles greater than 0 and less than the second intercept angle.

4.2.2 Wind Heeling Moment

The method of wind force and heeling moment calculation is based on the Coast Guard rules. The wind force is sensitive to the shape and projected area of the topside. In this stage of the conceptual study, except for the fuel load and off-loading purpose, the full function of the topside and associate equipment on it is not totally defined. Therefore, in order to reasonably estimate the wind force on the topside of the ASOP, a typical deck of offshore oil production platform is used in this study. The projected area of the deck is listed as follows:

	Projected Area	Center of pressure (above waterline)
Above drilling deck (deck house, rig and equipment)	9428 ft^2	148 ft
Between cellar and main deck	6186 ft^2	105 ft
Between subcellar and cellar deck:	3152 ft^2	69 ft

At the operational draft, the total wind heeling moment is 218,948 kips-ft for a 100 knot wind, and 54,737 kips-ft for a 50 knot wind. At transit draft (35 ft), the wind heeling moment is 289,642 kips-ft for a 100 knot wind.

4.2.3 Stability at Operational Draft

Figure 4.2 shows the intact righting moment curve and wind heel moment curve as a function of roll angle. The ASOP is at the operational draft (145 ft) and the wind speed is 100 knots (severe storm condition). Figure 4.3 shows the righting moment curve as a function of pitch angle. The righting moment curves for roll and pitch are very similar at small angles but different at larger angles due to the articulation discussed in section 4.1. Because of the large distance between the buoy and the center of the platform, the buoys at one side submerge into water completely at a relative small angle (9.5 degrees in roll), and no further buoyancy force is added by the buoys. Furthermore, the buoys at the other side will not keep vertical after a roll angle of 7.6 degrees and also greatly lose their contribution to the righting moment. Therefore, the righting moment reduces quickly when the roll is beyond 10 degrees and the range of roll angle of positive righting moment is much shorter than that of a conventional fixed column semi-submersible. In order to satisfy the stability criteria, a very large initial stability (or metacentric height) is required to ensure enough area under the righting moment curve. In the design, the ratio of the area under the righting moment curve and the wind heel moment curve is 1.6, which satisfies the stability criteria.

Following is a summary of the intact stability at the operational draft:

Draft	145	ft
Total Displacement:	452,865	kips
C.G. (above keel):	34.5	ft
C.B. (above keel):	30.9	ft
GMT:	8.57	ft
GML:	8.57	ft

4.2.4 Stability at Transit Draft

When the ASOP is at transit draft (35 ft), the hexagonal hull contributes to the stability of the platform. The righting moment is extremely large because of the large water plane area and second moment of the hull. Figure 4.4 shows the righting moment arm and wind heeling moment arm (for 100 knot wind speed) as a function of roll angle. The stability of the ASOP in the transit draft meets the stability criteria.

Following is a summary of the intact stability at the transit draft:

Draft	35	ft
Total Displacement:	294622	kips
C.G. (above keel):	37.9	ft
C.B. (above keel):	17.5	ft
GMT:	280.9	ft
GML:	280.9	ft

4.2.5 Free Surface Effects

At the operational condition, the soft storage tanks and most of the ballast tanks will be 100 percent full. Hard tanks will have a free surface most of the time, but those tanks have a relatively small free surface area and the reduction of the stability caused by the free surface effect is small. Assuming all the hard tanks and two of the ballast tanks have free surface, the reduction of the metacentric height (GMT) is 0.5 feet, or 6%.

At transit mode, the fuel storage tanks are either empty or 100 percent full. Free surface exists only in the ballast tanks and it has little influence on the stability due to the extreme large metacentric height. Assuming all the ballast tanks have free surface, the reduction of the height is only 0.7 feet, or 0.25%.

4.3 Damaged Stability

The damaged stability is a challenge to the ASOP concept due to its unique configuration. It is a key factor in determining the compartmentation of the hull and the buoys. Because of the large moment arm, any damage of the buoys and fuel storage tanks can cause considerable overturning moment, and in turn, cause large heeling angles and even capsize. The following are the possible damage conditions:

1) The buoys are damaged and flooded.
2) The center column is damaged and flooded.

3) The fuel storage tanks and the ballast tanks are damaged and flooded.

4) The universal joints are broken.

In our design, three criteria are established for damaged stability of the ASOP. They are as follows:

1) The platform will remain operational if any one buoy is damaged. The flooding will be limited to one third of the buoy's total volume. The stability must satisfy the Coast Guard rules and ABS rules for damaged condition.

2) The platform will remain operational if the center column is damaged. The flooding condition and damaged stability follows the Coast Guard rules and ABS rules .

3) In case any one universal joint is broken, or any one fuel storage tank is flooded, the platform will remain afloat with the topside above water line.

In order to satisfy the first and second criteria, each buoy is divided into 12 compartments by two horizontal watertight flats and two vertical watertight bulkheads, and the center column is divided into 16 compartments (Figure 4.5). According to the rules, four compartments (shadowed compartments in Figure 4.5) of a buoy may be subject to simultaneous flooding, and two of the compartments of the center column at the water line may be subject to simultaneous flooding. The damaged stability requirement of the Coast Guard and ABS is similar to the intact stability requirement except that the wind speed is reduced from 100 knots to 50 knots. Figure 4.6 shows the righting moment curve and wind heeling moment curve (50 knot wind speed) when the buoy is flooded. The damage stability satisfies the requirements of the Coast Guard and ABS. The flooding will also cause a heel of 2.1° and a draft increase of 1.9 ft. In the case of damage to the compartments in the center column, flooding will cause a change of draft about 3.7 ft, and a heel of about 0.35°. The flooding of the center column does not influence the stability because the contribution of the center column to stability is negligible, and the flooding is practically equivalent to adding more weight to the platform.

When a buoy is lost due to the failure of the universal joint and safety chains, an overturning moment applied suddenly will cause the platform to heel dynamically.

The maximum dynamic heeling can be much greater than the heeling when the platform reaches static equilibrium. Model tests showed that the maximum dynamic heeling angle is 1.5 times larger than the static heeling angle. The center column plays a important role in this condition by providing buoyancy and righting moment at large angles of heel. The equilibrium position of the platform after a buoy lost is:

Draft increase:	26.8 ft
Heeling angle:	33.7 deg

If one of the tanks in the lower hull is damaged, the most severe condition will occur if that tank is one of the soft tanks at the outside ring and full of fuel. The net weight gain by replacing the fuel in the tank with water is about 2.256 kips. The equilibrium position of the platform after the damage is:

Draft increase:	5.0 ft
Roll:	1.47 deg
Pitch:	6.16 deg

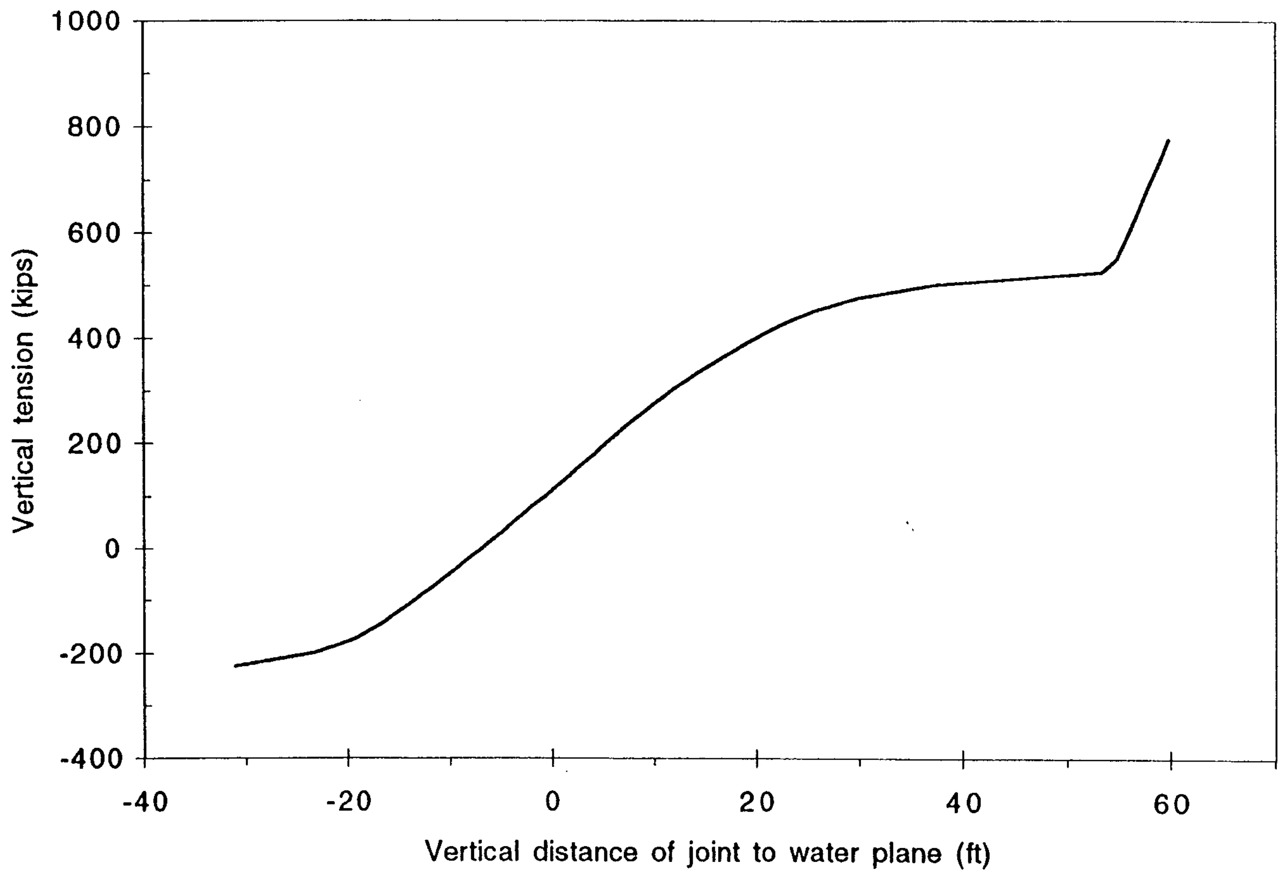


Figure 4.1 Vertical force at universal joint as a function of the vertical distance of joint to water plane (positive if the joint is under water)

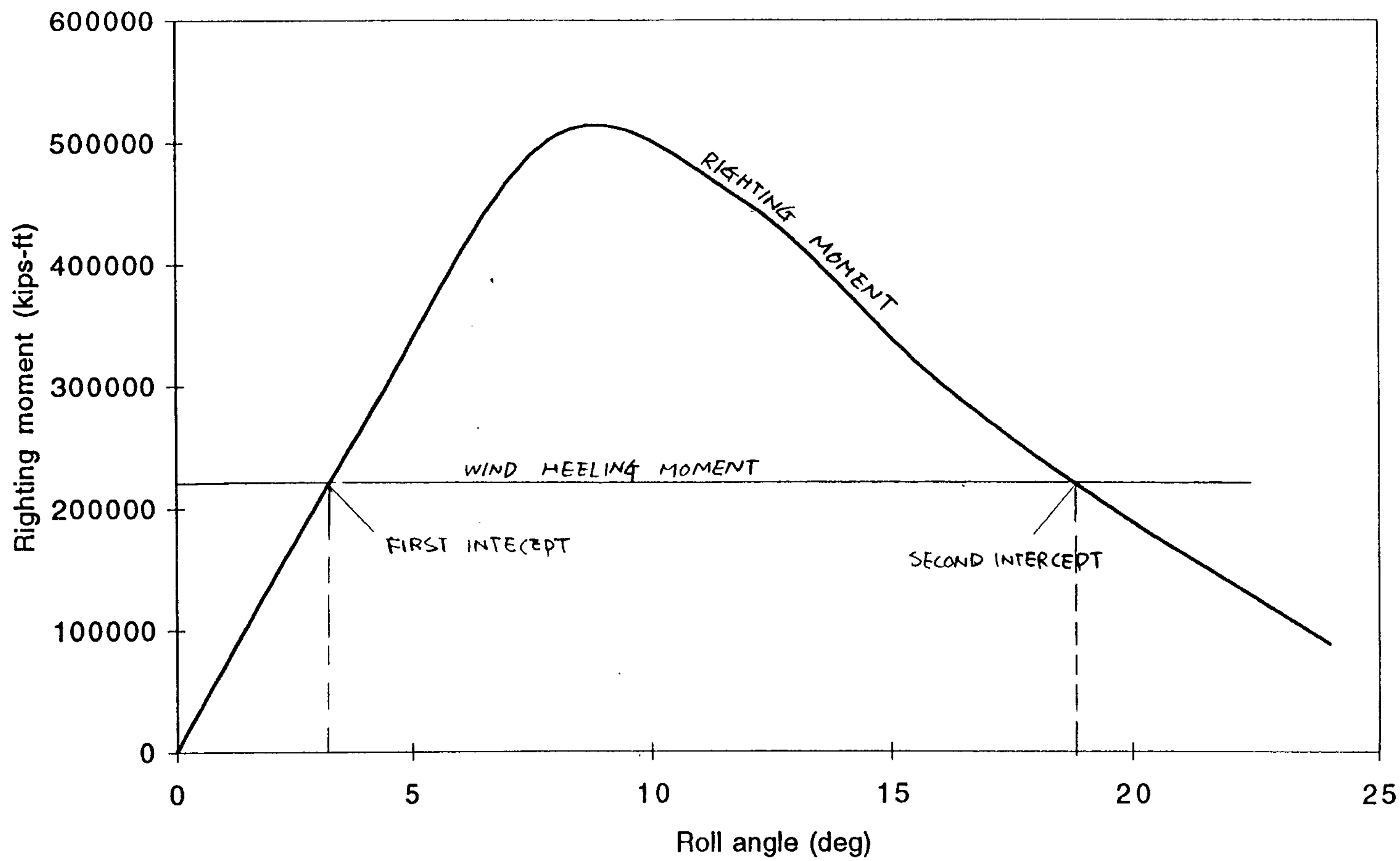


Figure 4.2 The ASOP intact stability curve (roll) at operational draft

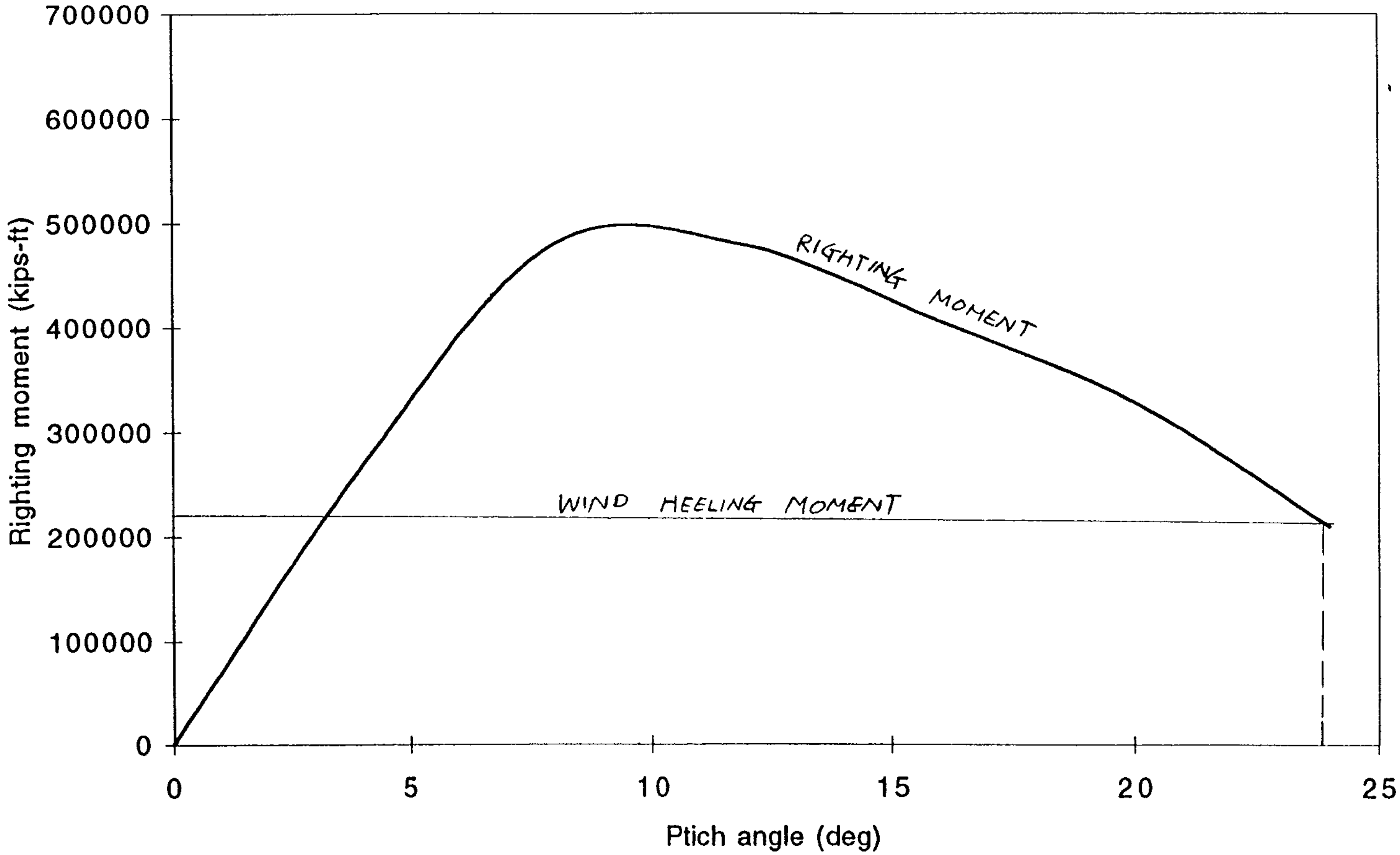


Figure 4.3 The ASOP intact stability curve (pitch) at operational draft

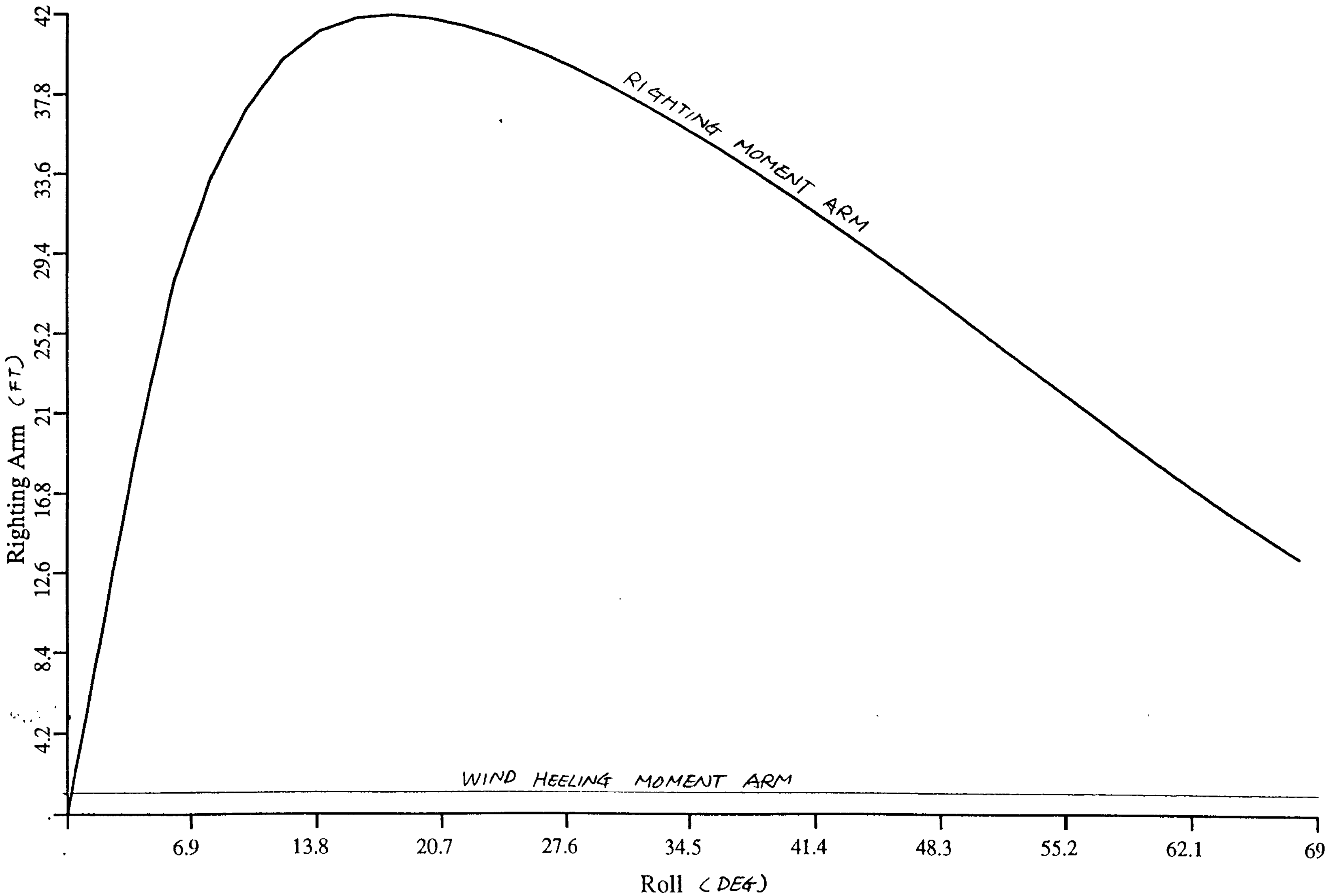


Figure 4.4 The ASOP intact stability curve at transit draft

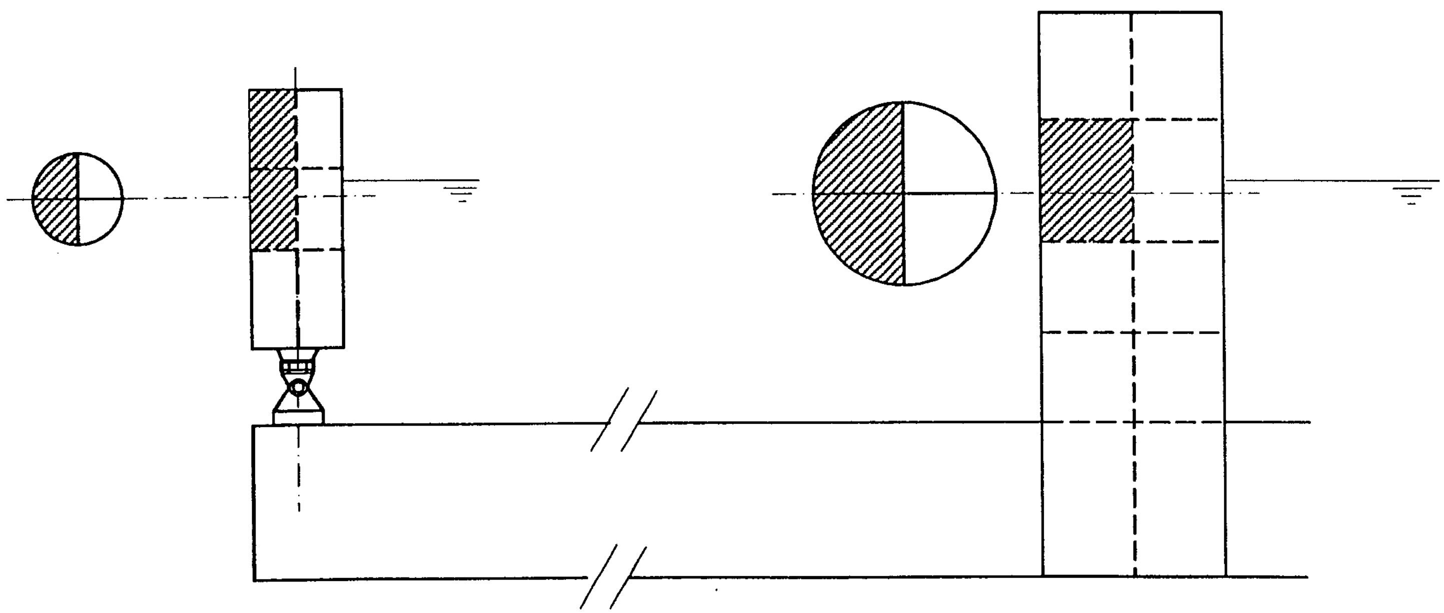


Figure 4.5   The location of the compartments subjected to flooding

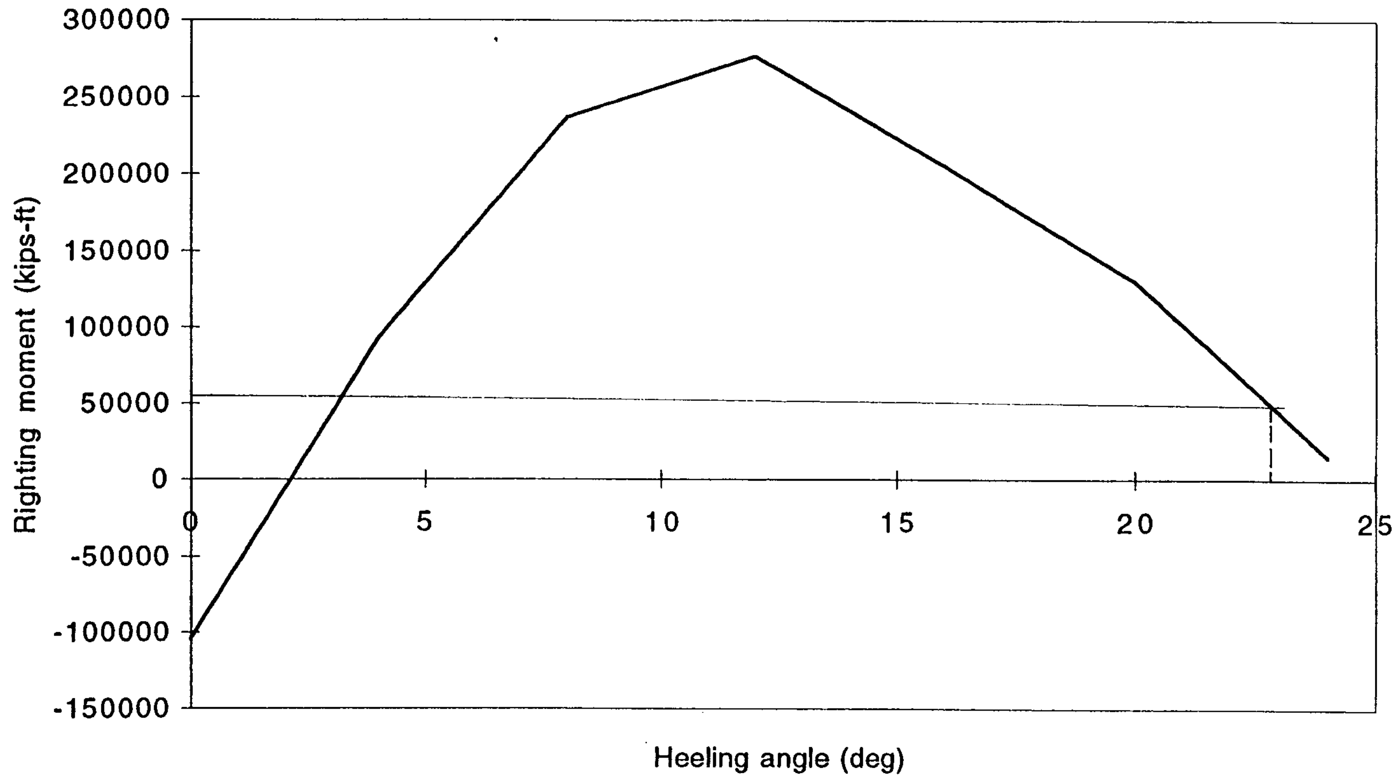


Figure 4.6 The ASOP damaged stability curve (buoy damaged)

CHAPTER 5 SEAKEEPING ANALYSIS

5.1 General

The motion of the ASOP in regular and random waves has been analyzed. At the operational draft, the platform is very stable even in severe wave conditions. The main hull is placed 95 ft below water (145 ft draft) and attracts much less wave force than that of a surface vessel. Furthermore, introducing articulation de-couples the rotational degree of motion of hull and buoy and, in turn, reduces the wave forces transmitted from the buoys to the main platform.

Linear diffraction analysis was performed for the main hull (hexagonal hull and center column) of the platform to obtain hydrodynamic coefficients such as wave exciting force, added mass and wave damping. Figure 5.2 shows the mesh generated for the diffraction analysis. The buoys were considered as slender bodies and the wave forces on them were predicted by Morison's equation, which includes an inertial force proportional to the water particle acceleration, and a nonlinear drag force proportional to the relative velocity squared. A typical six point mooring system is used for the station keeping of the platform. Figure 5.1 shows the stiffness of the mooring system. The water depth is assumed to be 700 ft. The motion of platform and buoys, together with the force on the universal joint and mooring line tension were analyzed both in frequency domain and time domain. A seven body coupled analysis, instead of a conventional single rigid body analysis, was used because the articulation allows relative motions between the hull and the buoys. All the analyses were performed with the computer program MOSES (Multi-Operation Structural Engineering Simulator), which was developed by Dr. R. Nachlinger of Ultramarine, Inc. in consultation with MEH.

In addition to the articulated cylindrical buoys, other buoy configurations and types of connections were also analyzed in order to fully understand the roles of buoys and the articulation in the global motion of the ASOP. They are:

1) The buoy is simply fixed to the hull which is equivalent to a column mounted on the hull. The objective was to find out whether the motion of the ASOP was improved by introducing articulation and allow the buoy to move in three rotational degrees of freedom.

2) The buoy is connected to the hull by a linear spring to further de-couple the motion of hull and buoy, and to reduce the force transmitted to the hull. The stiffness of the spring was 45 kips/ft.

3) Changing the buoy shape from cylindrical to hourglass. The buoy diameter was reduced linearly from 30 ft, at 30 ft below water line, to 22 ft at water line, and was linearly increased back to 30 ft at the top of buoy (30 ft above water line). The objective was to reduce the dimension of buoy near the water line and hence reduce the wave force on the buoy.

4) The center column is replaced by a jacket type structure to reduce the wave force on the main hull. Meanwhile, the diameter of the buoys was increased from 30 ft to 39 ft so that the total water plane area remain unchanged.

The detailed description of the above buoy configurations and their mass properties can be found in the model test report from Offshore Model Basin (OMB), "Model Studies of Articulated Stable Ocean Platform, Preliminary Report No. OMB-95-214-1".

5.2 Natural Periods

The natural periods of the platform were obtained by time domain free decay simulation. The analysis indicated that the natural periods in surge, heave and pitch were 214.2, 88.0 and 68.2 seconds, respectively. Those natural periods are far beyond the range of wave energy thus the motion at the wave frequency is expected to be small. However, the buoys have a pitch natural period of 14.1 seconds which is within the frequency where wave energy exists. Although it is better to have the natural period of the buoy out of the wave energy range, in order to do so, the buoy will have a much larger weight which in turn will reduce the contribution of the buoys to the stability of the platform. This is a typical case of compromising between motion and stability. Figures 5.3 to 5.6 show the simulated surge, heave, pitch and buoy pitch free oscillations .

5.3 Frequency Domain Analysis

The response amplitude operators (RAO, the motions or force amplitude correspondence to unit amplitude wave) of the motion, connector force, and mooring line tension were calculated in the frequency domain. Nonlinear viscous forces were linearized using equivalent energy method (the work done by nonlinear drag force in a wave period is equivalent to the work done by the linearized drag force). The wave period range was from 5.5 seconds to 25 seconds. Two wave headings --0 and 90 degree -- were studied. The results shows little difference between the two headings due to hull symmetry. Therefore, only the results for 0 degree wave heading are presented in this report.

Figures 5.7 to 5.9 show the surge, heave and pitch RAO of the platform, respectively. Figure 5.10 shows the vertical force at the universal joint (buoy #1 in Figure 6.2). Figure 5.11 shows the mooring line tension (ML1 in Figure 6.2). The results indicate that there were improvements in the forces at the buoy--hull connection by using spring connection and hourglass shaped buoys, but motion and mooring line tension were very similar among all the configurations. Also, there was no significant difference in the overall motion and mooring line tension between the platforms with fixed buoys and articulated buoys. The surge was slightly improved (less than 4%) by using articulation but the pitch motion was increased compared to the fixed buoys configuration. In general, improvement of motion by using articulation, spring connection and changing buoys shape was insignificant. Because of the large under water volume of the lower hull, the motion of the ASOP is dominanted by the mass of the hull and the wave force on the hull, not the buoys. For example, in the regular wave with 12 second period, the wave force on all six buoy was only 17.60% of the wave force on the hull in surge, 5.27% in heave and 0.77% in pitch. Introducing articulation and other buoy configurations did not change the wave force on the hull significantly hence having little effect on the motion of the platform. Compared to the cylindrical buoys, the hourglass shaped buoys reduced the vertical force transmitted to the hull by 50% (60 kips) in the regular wave with 12 second wave period, but that only changed the total heave force on the hull by 1.8% and was not efficient in improving the motion of the platform.

The model test results in regular waves are also presented in those figures. We saw good agreement between the numerical analysis and the model test in heave response, vertical force at the buoy - hull connection and mooring line tension. There was some discrepancy in the surge and pitch response (about 20% difference) but the trend of the response varying with wave frequency was very similar. The model test also indicated that there was no significant difference in motion and mooring line tension among the different configurations.

5.4 Time Domain Simulation

Like other compliant type offshore platforms such as the semi-submersibles which have very long natural periods, the ASOP was dominanted by slow drift motions. The slow drift motion is the motion of a platform at its natural frequencies due to nonlinear wave forces. One of the nonlinear wave forces is the slow drift force which is generated by interactions between wave components of different periods. Although an order of magnitude smaller than the wave frequency force, the drift force has very long periods and can cause resonant response of the platform. Usually the magnitude of slow drift motion of the platform is much larger than that of waves frequency motion and is very important for mooring system design. Another typical nonlinear force is the velocity squared drag force. Frequency domain analysis predicts the wave frequency (linear) motion with accuracy, but it may give gross error for the drift motion because the nonlinearities can not be included in the analysis. Therefore, time domain analysis, which can include the nonlinear effects, is usually used to predict the motion of platform in random waves.

The motion of the ASOP was simulated in time domain for two extreme wave conditions -- a 10 year storm and a 100 year storm. The waves were assumed to be unidirectional (long-crested) and the wave heading was 0°. The wave energy distribution followed the JONSWAP spectrum formula with appropriate significant wave height, peak spectrum period and over-shooting parameter. For the 10 year storm, the significant wave height was 20 ft, peak period was 11 seconds and overshooting parameter was 2. For the 100 year storm, the significant wave height was 39 ft, peak period was 14.1 seconds and overshooting parameter was 2. Wind and current force, which are usually modeled as steady forces and only cause a steady offset of the platform, were not considered in the analysis. The duration of the simulation was one hour, and the time step was 0.5 second. The Newmark-Beta integration scheme, which is a unconditional stable with second order accuracy, was used in the simulation. After the simulation, the statistics of the time series, including motion of the platform, force on the buoy-hull connection and mooring line tension were obtained. In addition, to better understand the motion characteristics, the high frequency and low frequency filter was used to separate the wave frequency response and slow varying response and the statistics for both components were obtained.

Figures 5.12 and 5.13 show the numerically generated wave and its energy spectrum. Figures 5.14 to 5.19 show the simulated time history and spectra of the ASOP's surge, heave and pitch response. The simulation has also been done for the same platform with fixed buoys instead of hinged buoys in order to see the effects of articulation. Tables 5.1 and 5.2 list the statistics of the numerical simulation together with the model test results.

Both the numerical and model test results show that there are significant slow drift motions for the ASOP in random waves. For the 10 year storm condition, the numerical simulation in general agrees with the model test results except that the slow drift heave motion was smaller than that of the model test. For the 100 year storm condition, although wave frequency responses were very close, there were some discrepancies in mean and slow drift responses between simulation and model test. This shows that accurate prediction of the nonlinearities in numerical analysis is still a challenge. By fixing the buoys to the hull, the slow drift motion of the platform was greatly reduced. The reason for this was that the large angle pitch motion of the buoys introduced more nonlinear forces into the system and, in turn, created larger drift motions. The model test results gave similar conclusions but the reduction of the drift motion by fixing the buoys was insignificant.

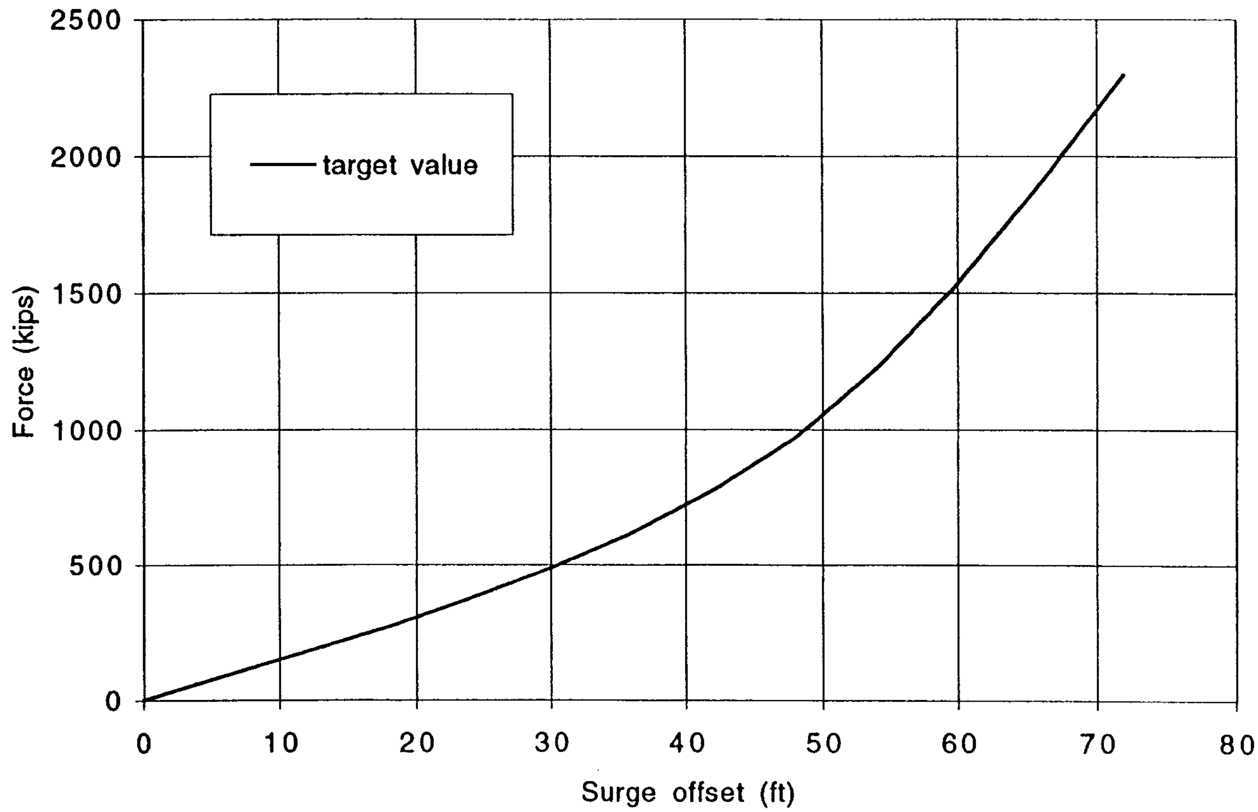


Figure 5.1 Mooring stiffness in surge direction

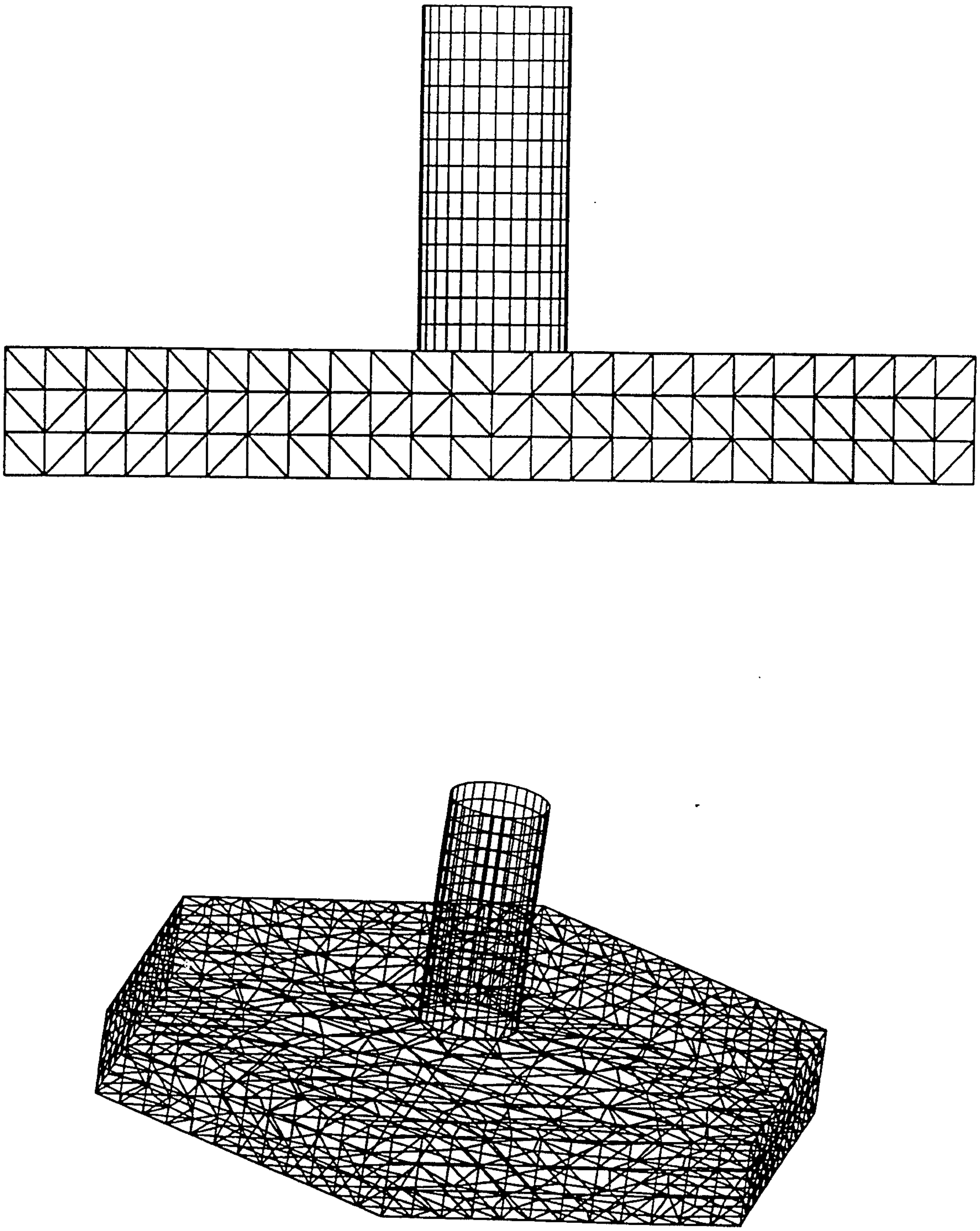


Figure 5.2 Mesh generated for the diffraction analysis

Figure 5.3 The ASOP surge free decay simulation

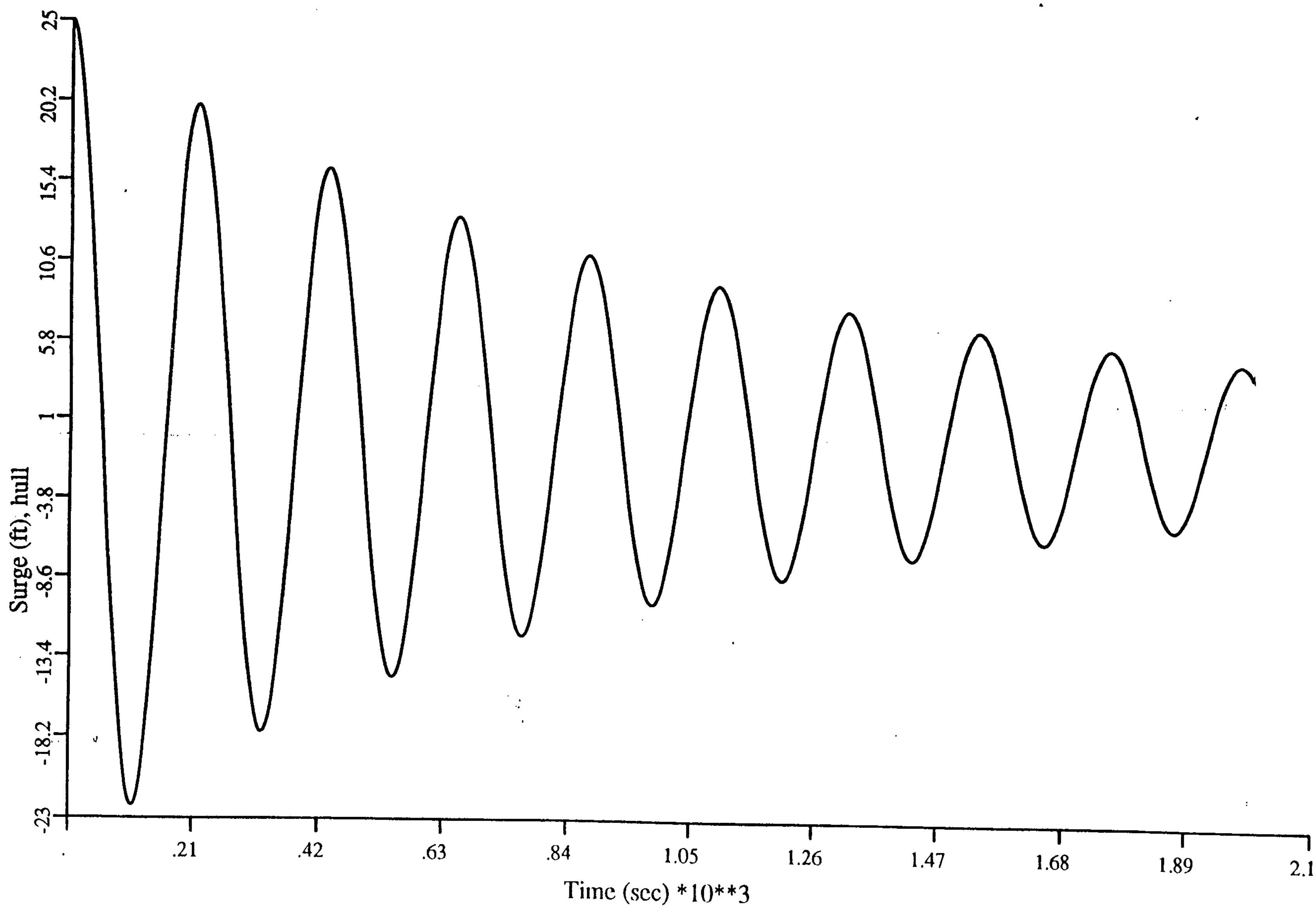


Figure 5.4 The ASOP heave free decay simulation

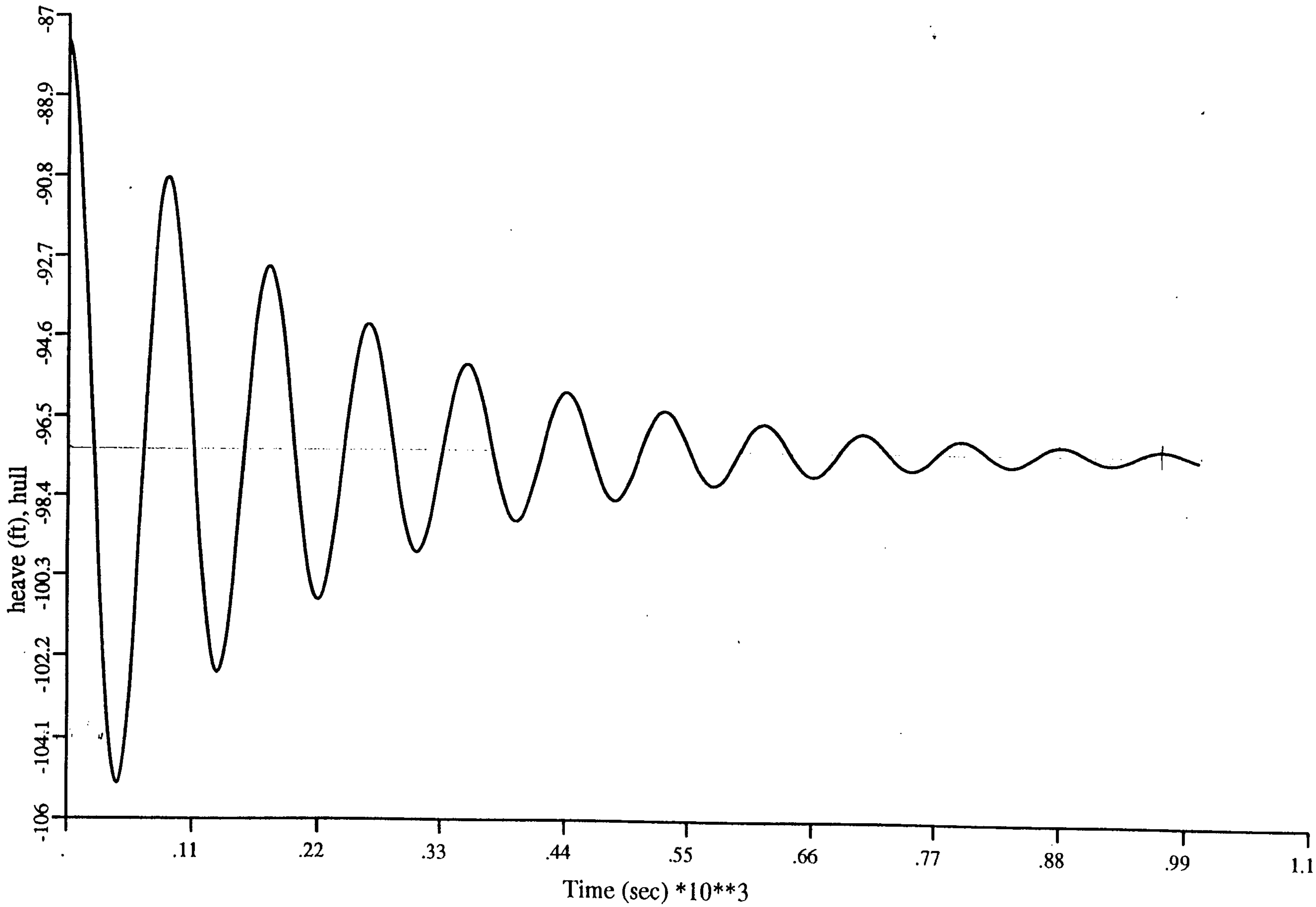


Figure 5.5 The ASOP pitch free decay simulation

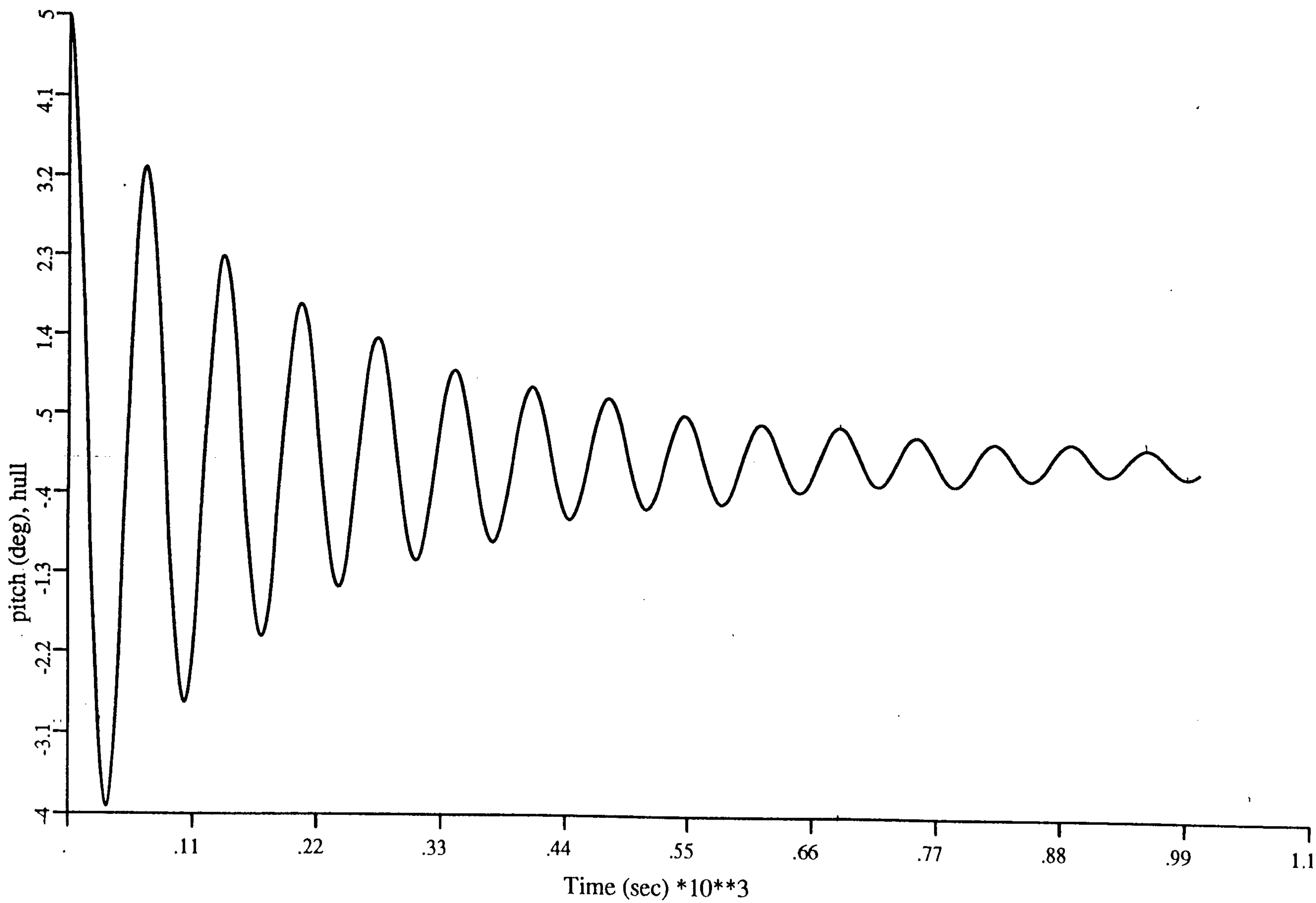
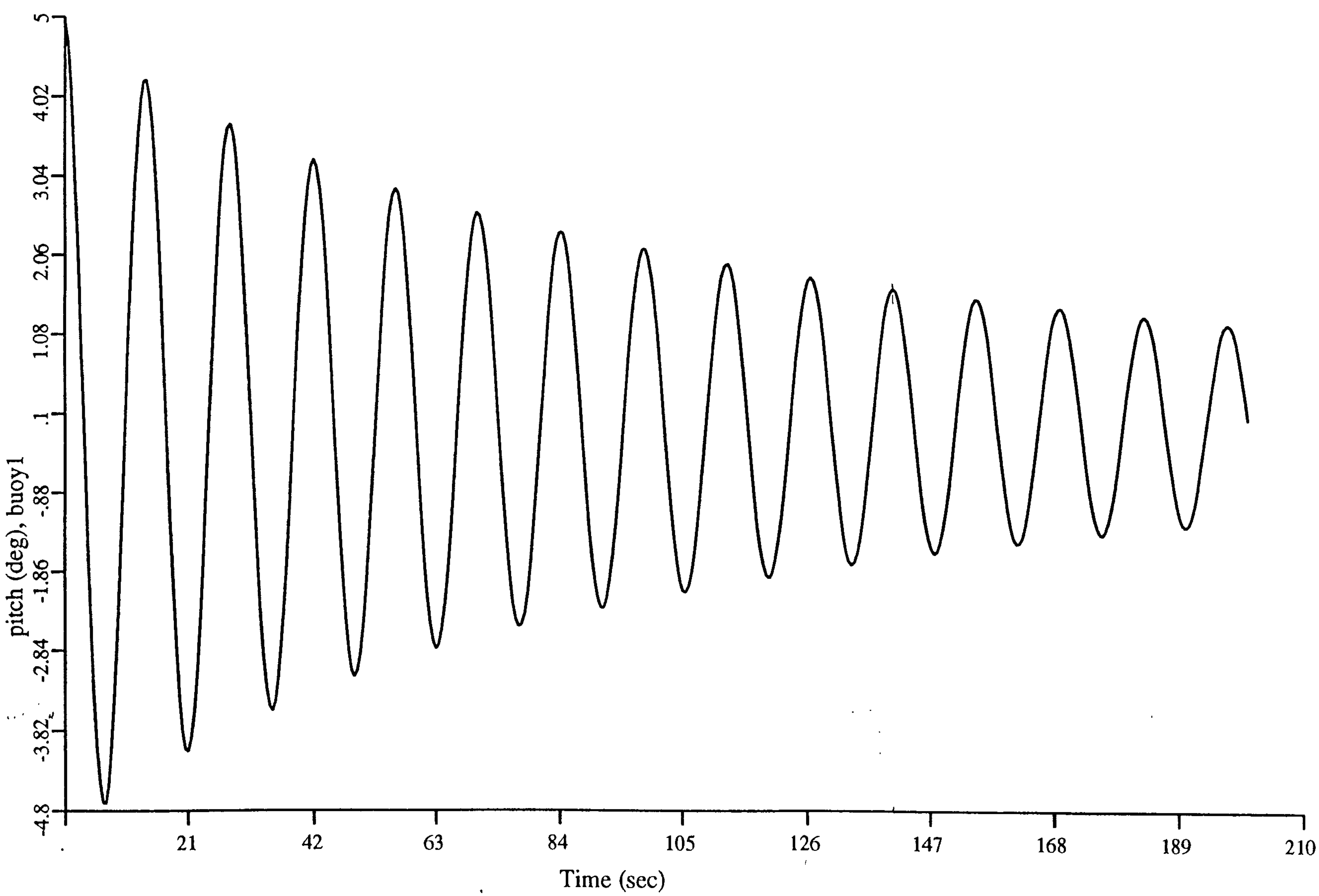


Figure 5.6 The buoy pitch free decay simulation



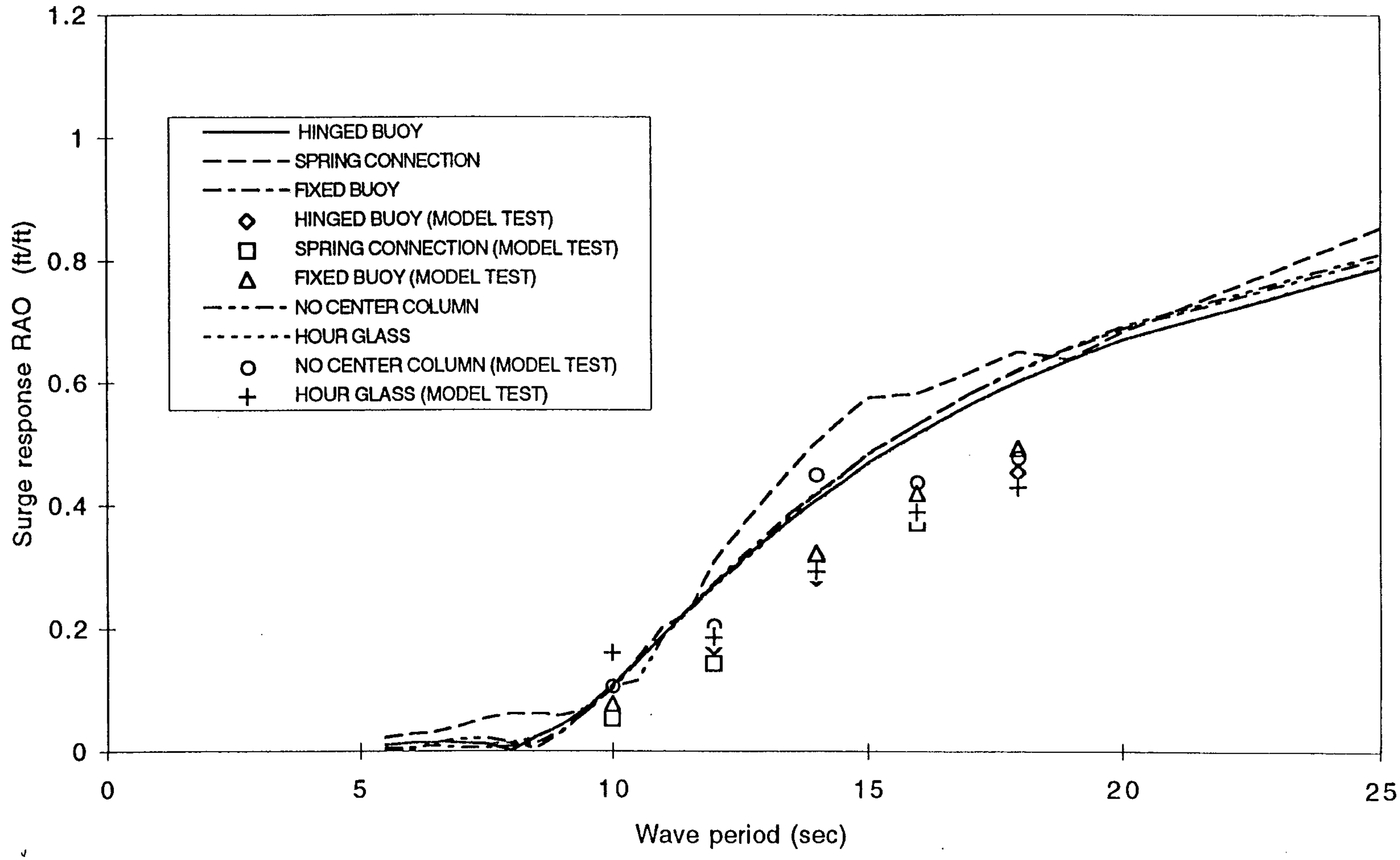


Figure 5.7 Frequency domain analysis. Surge response RAO

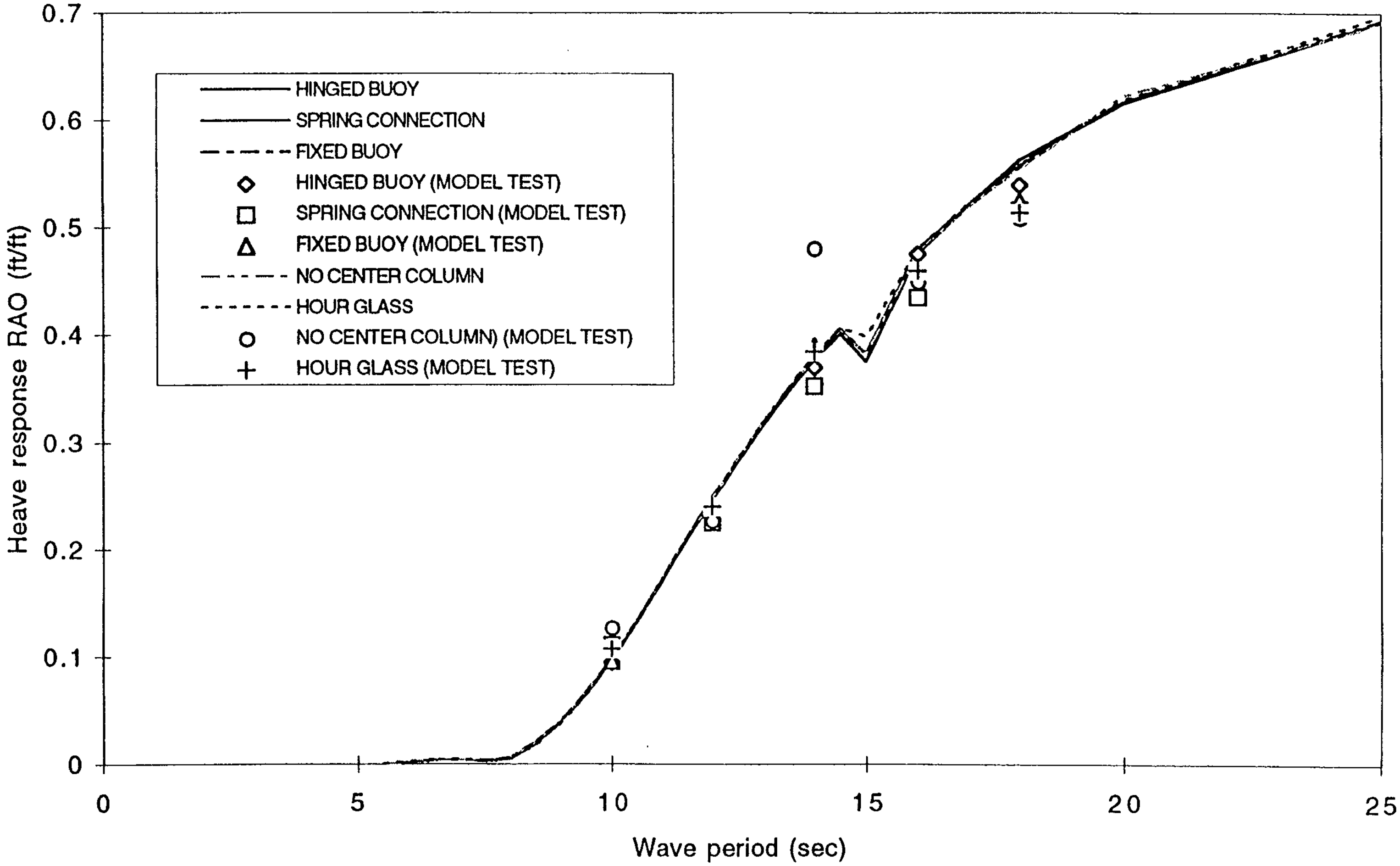


Figure 5.8 Frequency domain analysis. Heave response RAO

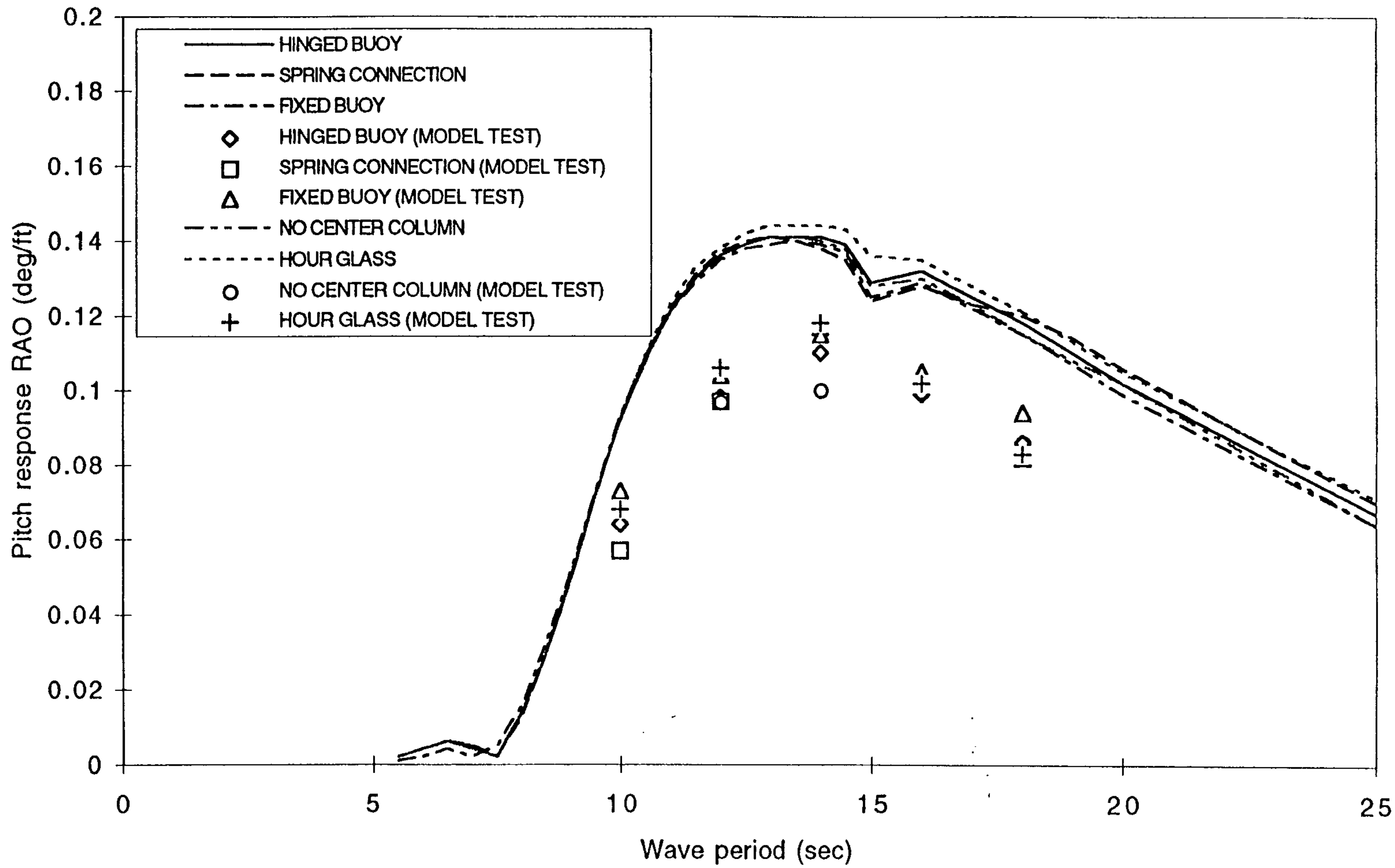


Figure 5.9 Frequency domain analysis. Pitch response RAO

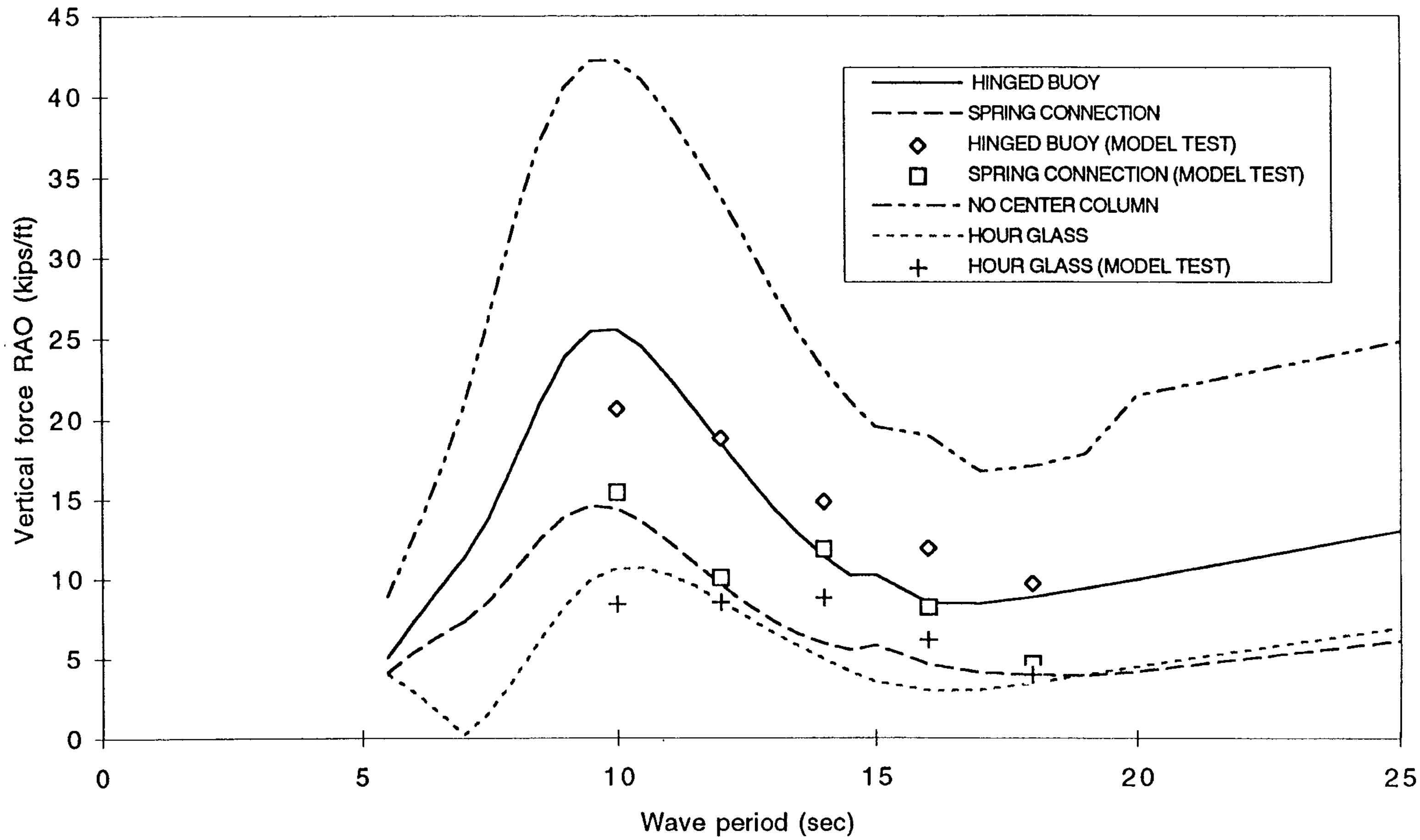


Figure 5.10 Frequency domain analysis. Vertical force on the buoy-hull connection

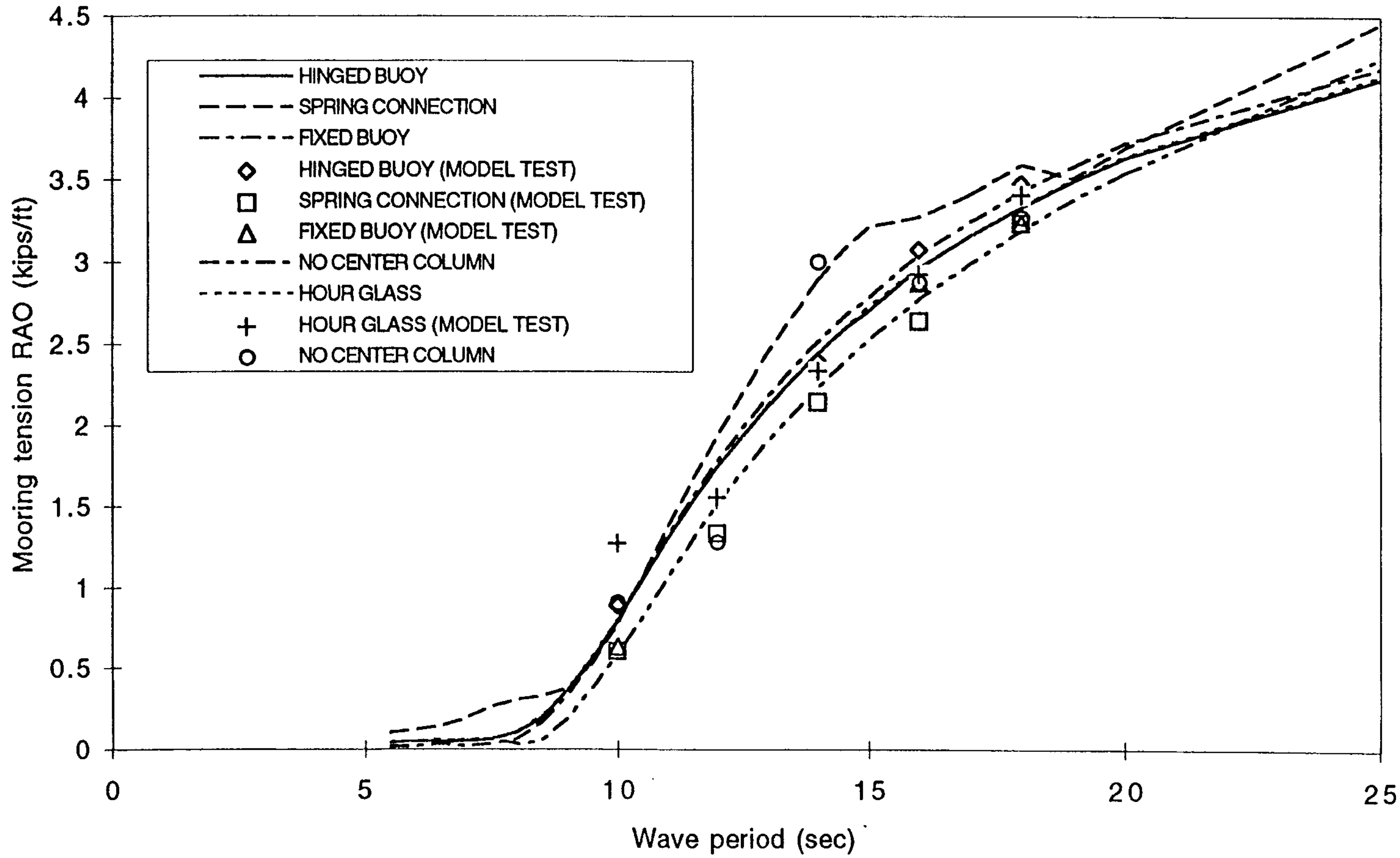


Figure 5.11 Frequency domain analysis. Maximum mooring line tension RAO

Figure 5.12 Time series of the simulated random wave elevation (100 year storm)

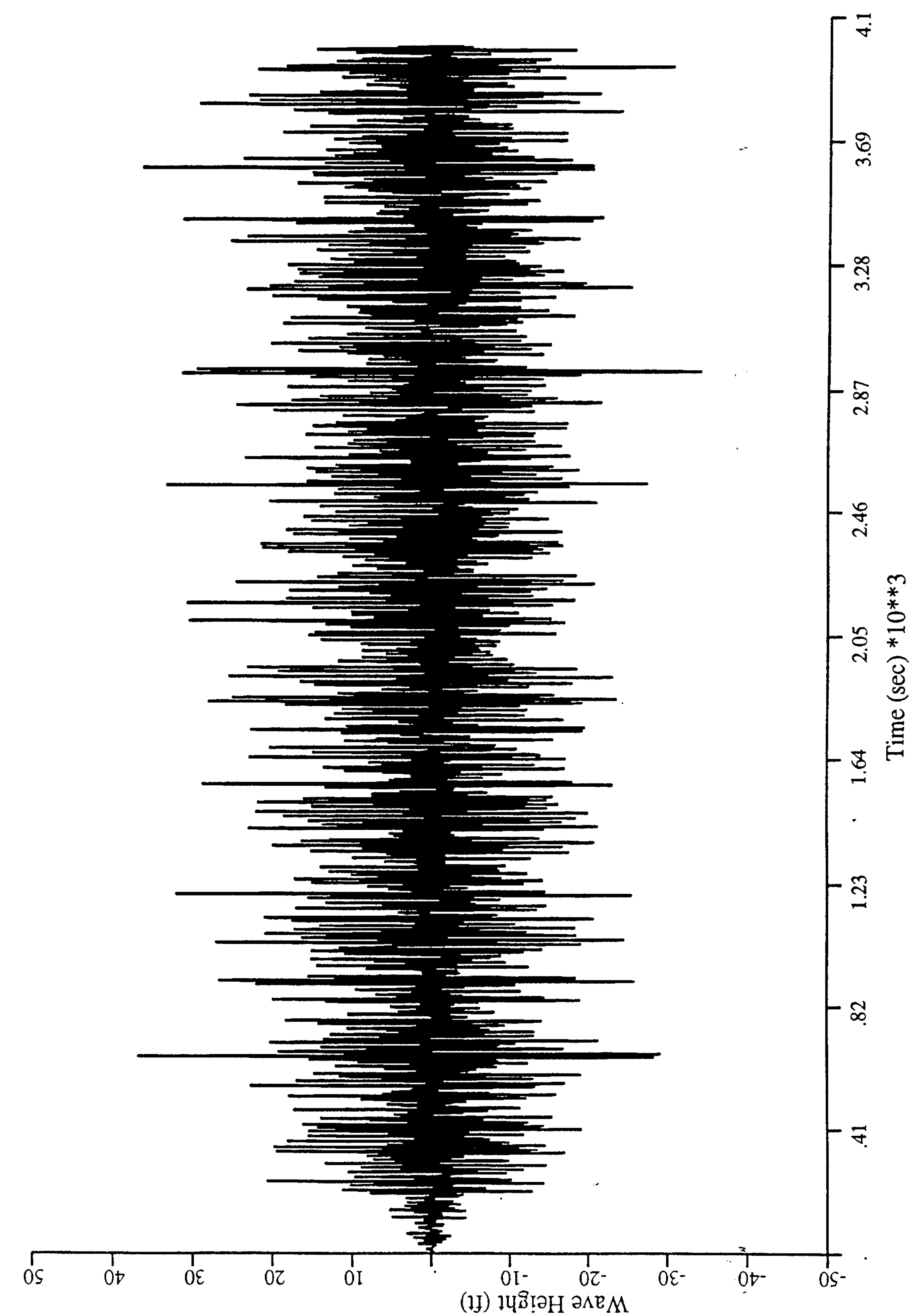


Figure 5.13 Energy spectrum of the simulated random wave (100 year storm)

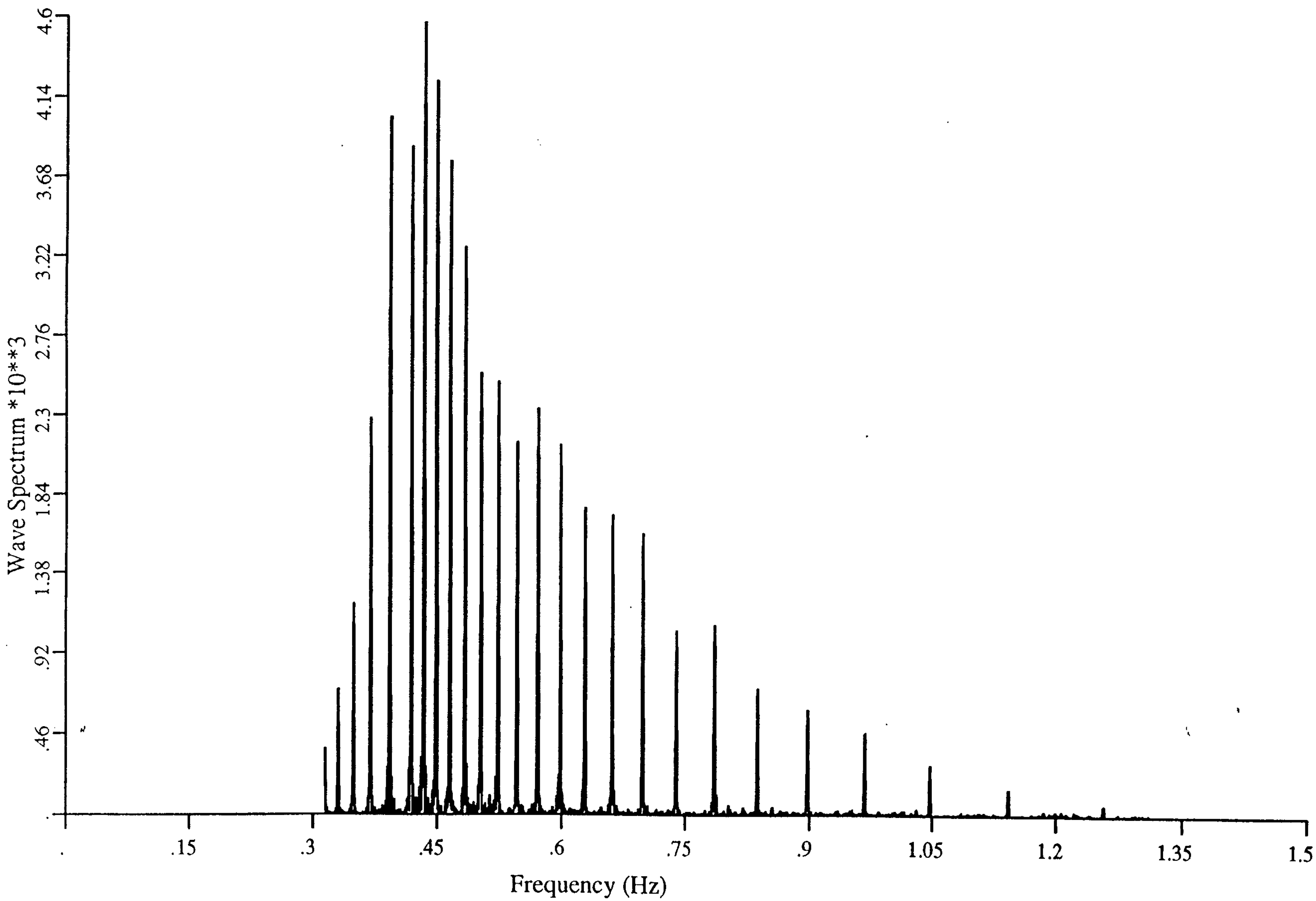


Figure 5.14 Time series of the simulated surge motion of the ASOP in 100 year storm.

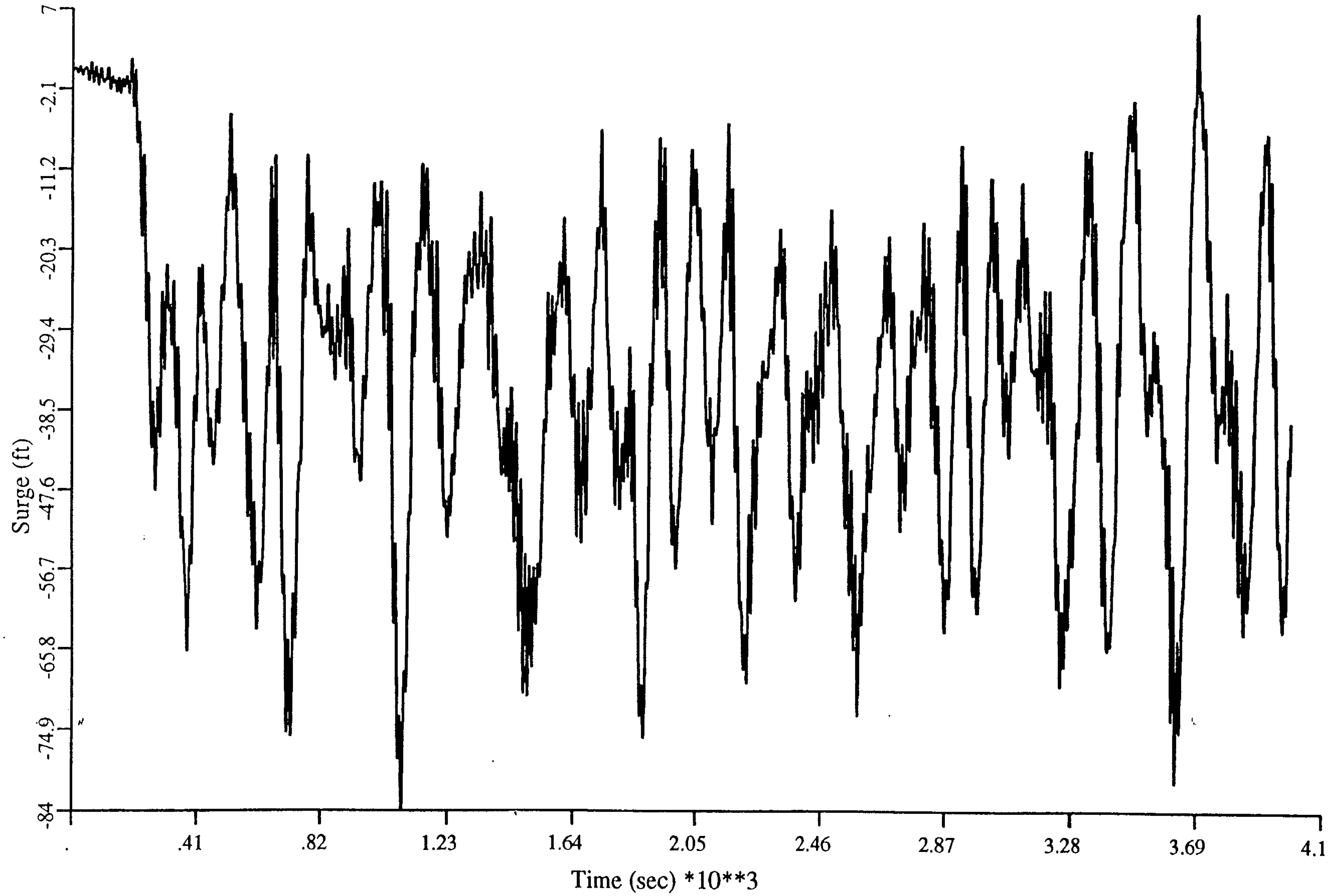


Figure 5.15 Energy spectrum of the simulated surge motion of the ASOP

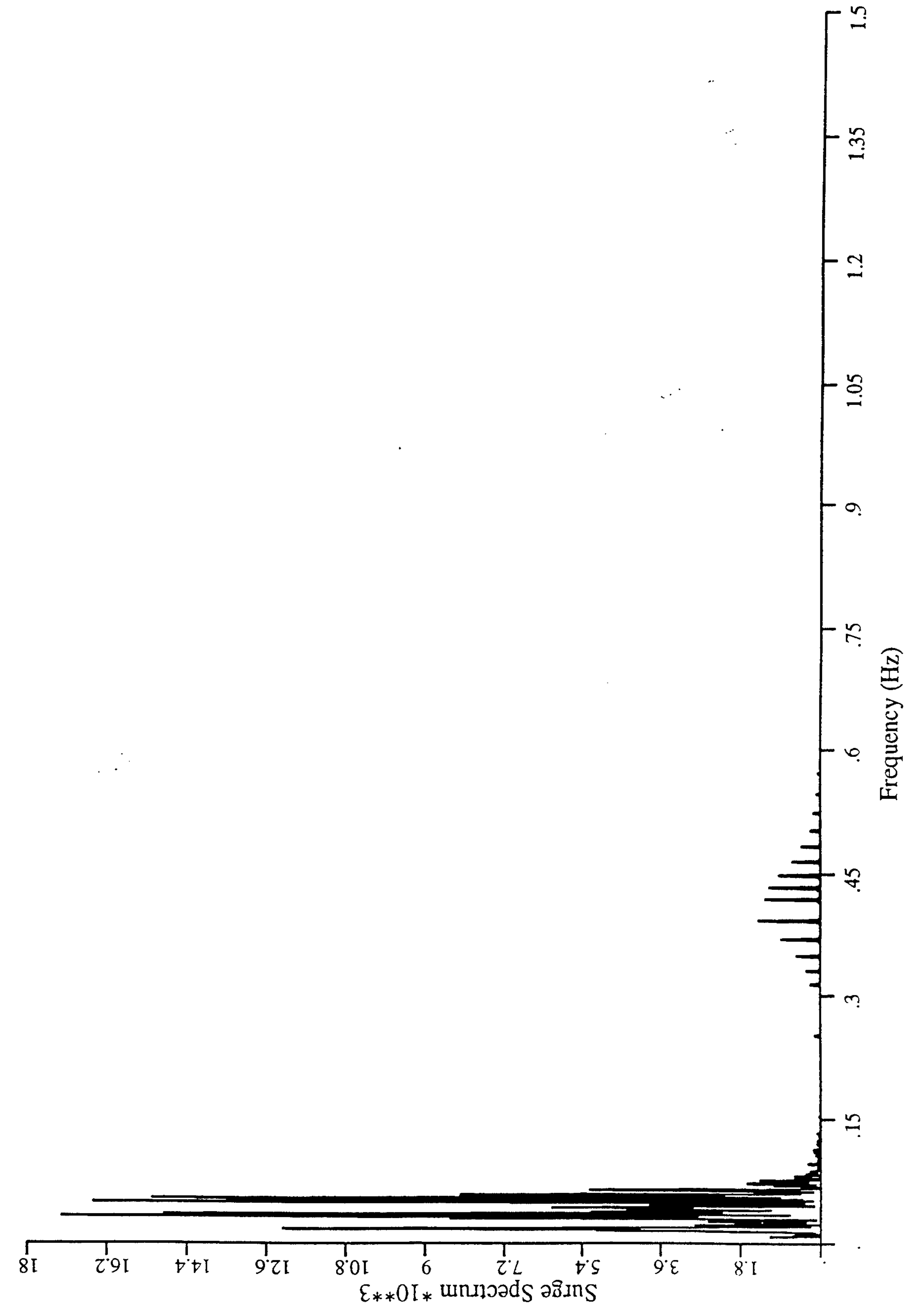


Figure 5.16 Time series of the simulated heave motion of the ASOP in 100 year storm.

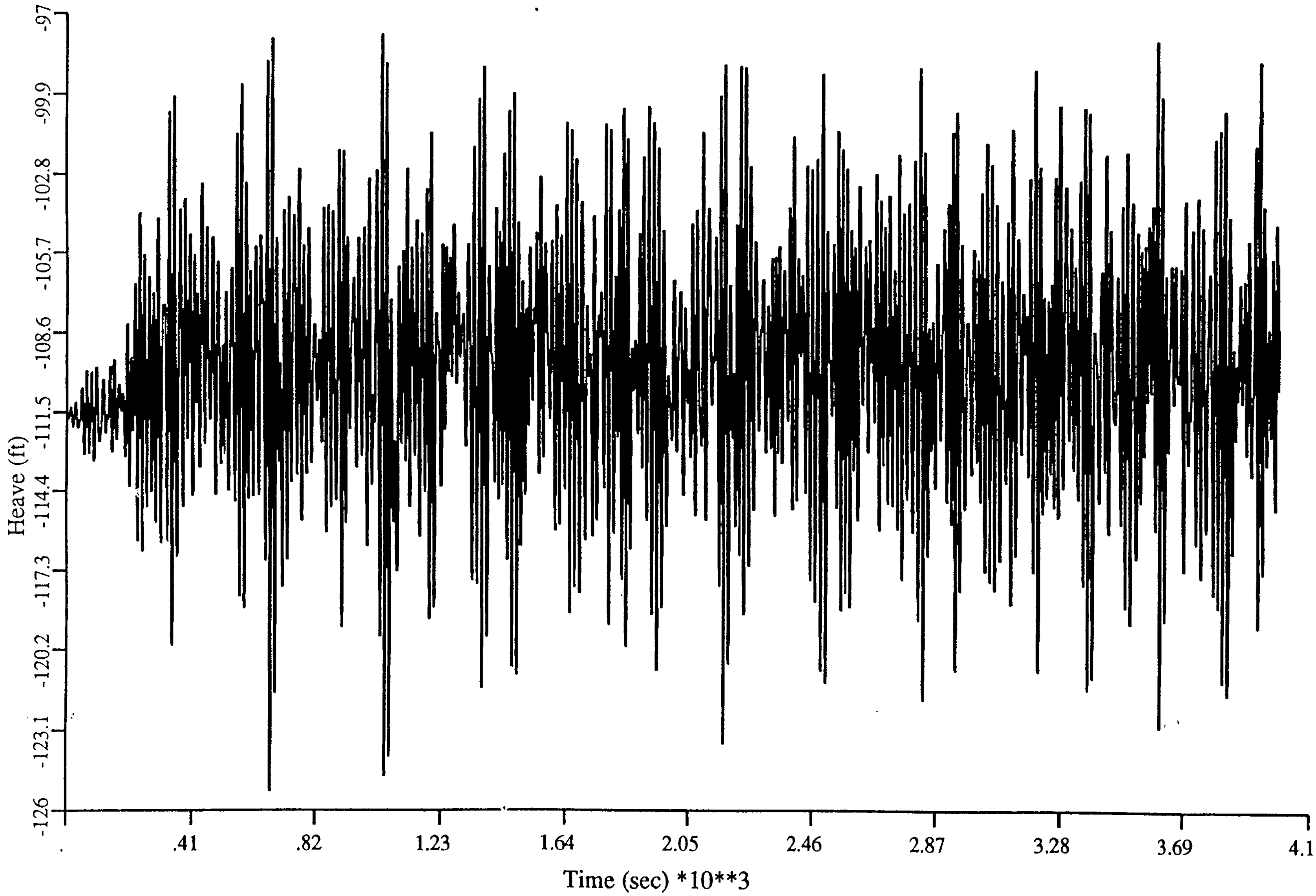


Figure 5.17 Energy spectrum of the simulated heave motion of the ASOP

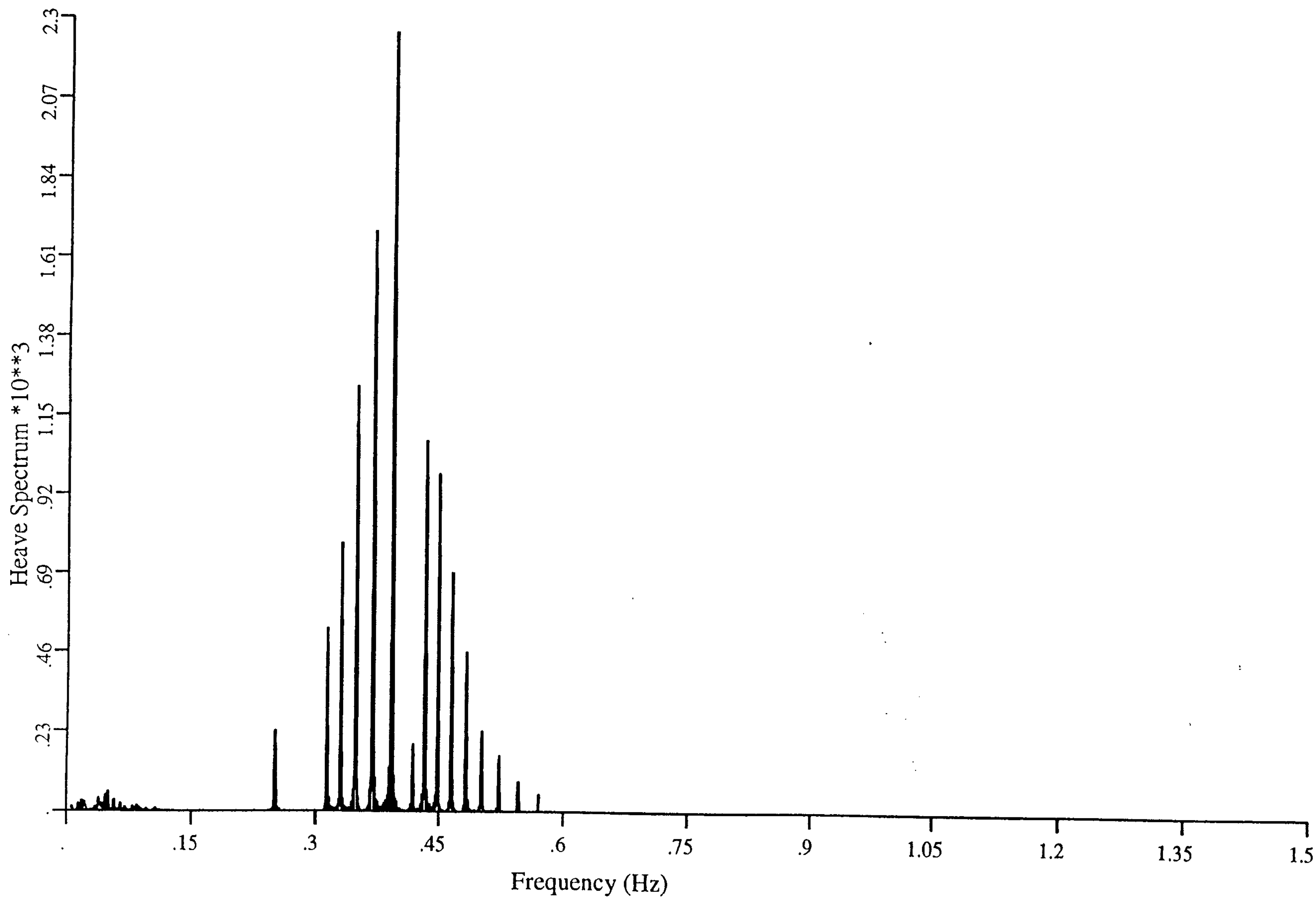


Figure 5.18 Time series of the simulated pitch motion of the ASOP in 100 year storm.

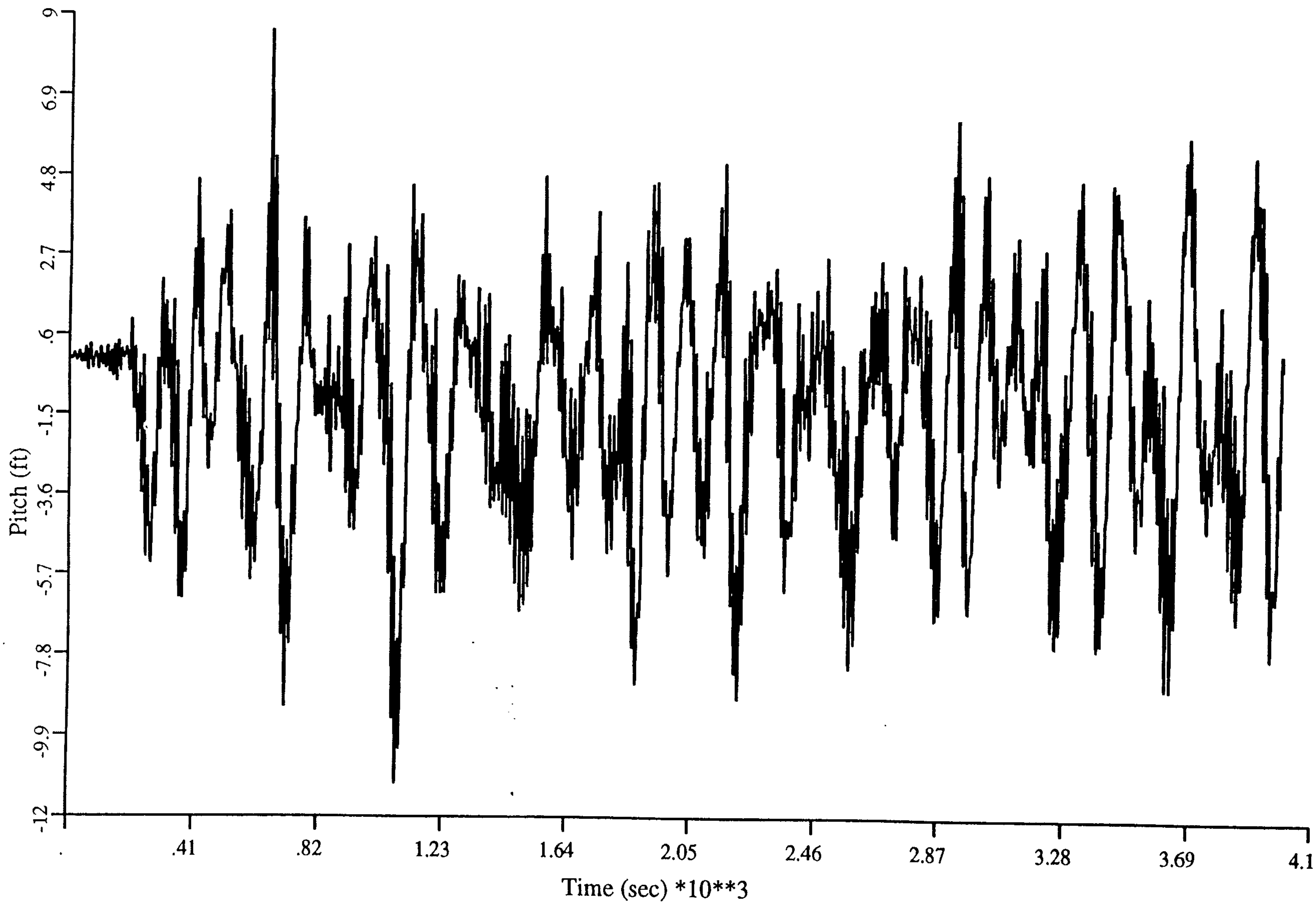


Figure 5.19 Energy spectrum of the simulated pitch motion of the ASOP

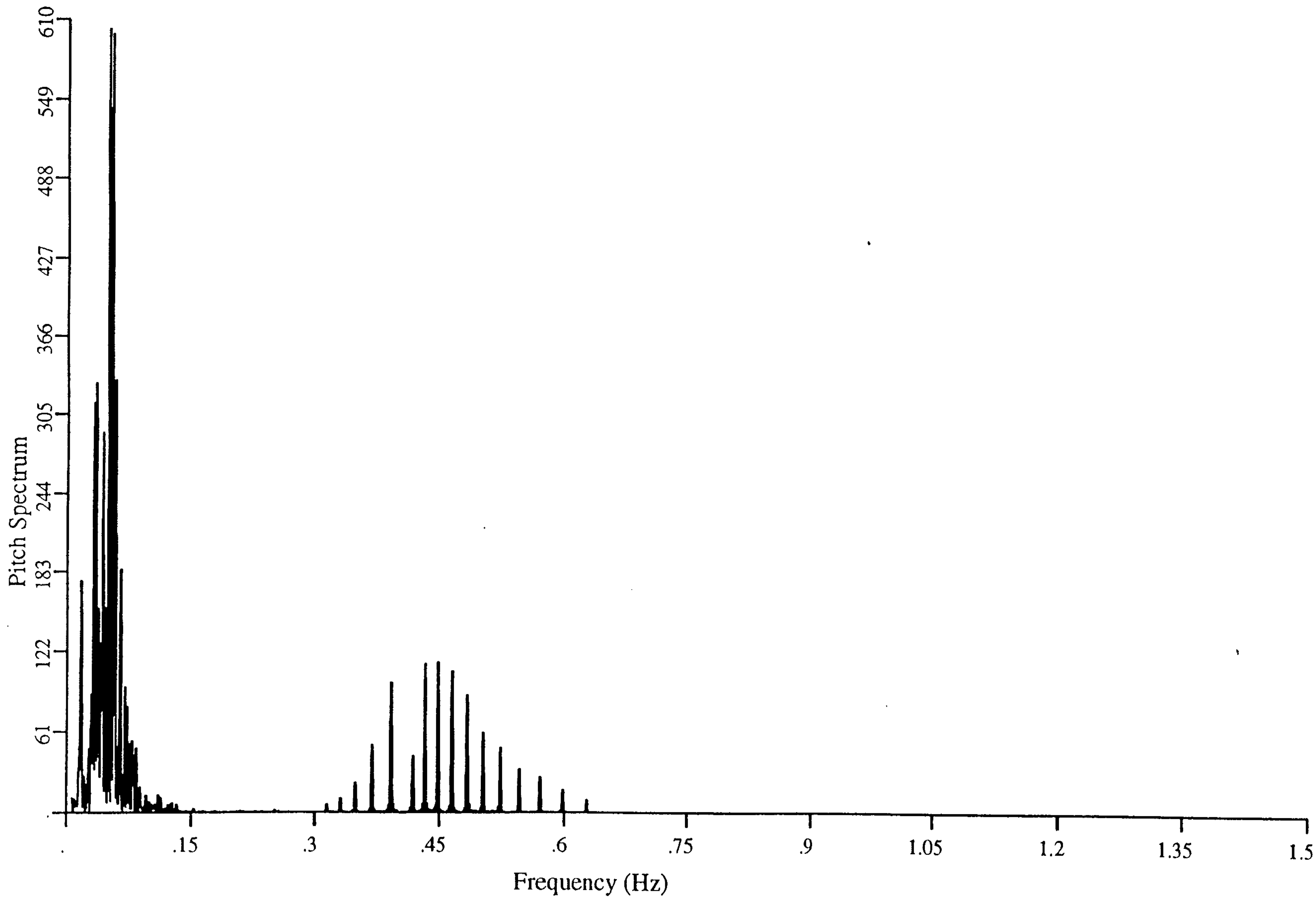


Table 5.1 Statistics of the time domain simulation of the ASOP in 100 year storm

(Hs=39ft, Tp=14.1sec, Gamma=2, JONSWAP)

	ARTICULATED BUOYS		FIXED BUOYS	
	SIMULATION	MODEL TEST	SIMULATION	MODEL TEST
WAVE ELEVATION: (FT)				
MEAN	-0.04	-0.08	-0.02	-0.05
MAX.	37.10	46.64	36.53	51.07
MIN.	-34.09	-41.59	-33.72	-41.28
RMS	9.73	10.82	9.72	10.73
SURGE AT CG: (FT)				
MEAN	-36.81	-17.70	-8.67	-11.62
MAX.	6.77	29.99	7.01	25.49
MIN.	-83.99	-55.86	-30.86	-51.31
RMS	15.93	13.90	6.48	12.57
RMS(L)	15.45	13.57	5.16	12.16
RMS(H)	3.97	3.04	3.91	3.18
HEAVE AT CG: (FT)				
MEAN	1.92	1.86	0.91	0.70
MAX.	14.07	22.41	11.68	26.65
MIN.	-13.65	-19.52	-16.03	-19.29
RMS	4.49	5.91	4.40	5.96
RMS(L)	0.96	4.58	0.58	4.59
RMS(H)	4.38	3.73	4.36	3.80
PITCH: (DEG)				
MEAN	-1.27	-0.51	-0.15	-0.17
MAX.	8.60	4.15	5.58	7.12
MIN.	-11.15	-8.10	-4.29	-6.38
RMS	2.90	1.60	1.40	1.44
RMS(L)	2.61	1.17	0.76	0.99
RMS(H)	1.25	1.08	1.18	1.05
MAX. MOOR TENSION: (KIPS)				
MEAN	726.50	465.27	331.43	346.84
MAX.	2547.10	1424.88	529.50	1065.92
MIN.	256.13	139.19	245.24	120.88
RMS	375.58	169.17	43.96	105.00
VERTICAL FORCE AT JOINT 1: (KIPS)				
MEAN	1728.97	1818.33		
MAX.	5190.31	2820.74		
MIN.	213.31	494.17		
RMS	447.41	332.22		
VERTICAL FORCE AT JOINT 2: (KIPS)				
MEAN	1788.33	1819.27		
MAX.	3984.30	2753.35		
MIN.	793.06	661.20		
RMS	335.60	267.60		

Table 5.2 Statistics of the time domain simulation of the ASOP in 10 year storm

(Hs=20ft, Tp=11sec, Gamma=2, JONSWAP)

	ARTICULATED BUOYS		FIXED BUOYS	
	SIMULATION	MODEL TEST	SIMULATION	MODEL TEST
WAVE ELEVATION: (FT)				
MEAN	-0.02	0.33	-0.02	0.29
MAX.	18.48	26.65	18.25	22.86
MIN.	-15.85	-18.65	-17.95	-19.89
RMS	5.02	5.57	5.01	5.52
SURGE AT CG: (FT)				
MEAN	-13.99	-6.16	-0.41	-2.58
MAX.	3.67	15.68	3.28	15.19
MIN.	-45.73	-34.96	-3.55	-18.52
RMS	7.75	8.37	1.08	6.18
RMS(L)	7.68	8.32	0.44	6.12
RMS(H)	1.02	0.84	0.98	0.82
HEAVE AT CG: (FT)				
MEAN	1.63	1.09	0.10	0.33
MAX.	5.86	13.68	3.06	10.24
MIN.	-1.68	-9.26	-3.52	-7.22
RMS	1.15	4.04	0.97	2.82
RMS(L)	0.62	3.93	0.05	2.63
RMS(H)	0.97	0.96	0.97	1.02
PITCH: (DEG)				
MEAN	-0.35	-0.06	0.00	-0.11
MAX.	3.25	3.55	1.83	2.17
MIN.	-6.20	-3.64	-1.43	-2.44
RMS	1.30	1.36	0.46	0.73
RMS(L)	1.21	1.29	0.07	0.58
RMS(H)	0.47	0.44	0.45	0.44
MAX. MOOR TENSION: (KIPS)				
MEAN	374.06	354.42	282.37	300.00
MAX.	773.71	743.58	302.96	391.93
MIN.	266.74	216.11	264.14	212.45
RMS	67.90	65.36	6.30	32.31
VERTICAL FORCE AT JOINT 1: (KIPS)				
MEAN	1705.75	1871.24		
MAX.	3292.97	2626.21		
MIN.	893.82	1132.22		
RMS	249.99	255.59		
VERTICAL FORCE AT JOINT 2: (KIPS)				
MEAN	1705.99	1846.19		
MAX.	3213.01	2472.78		
MIN.	1206.54	1256.98		
RMS	189.78	196.26		

CHAPTER 6 MODEL TEST

6.1 General

Model testing was a major part of this conceptual study. The model test program was designed to aid in determining the feasibility of the Articulated Stable Ocean Platform (ASOP) concept, and to reinforce the computational analysis. The main objective of this test was to find the motion characteristics of the ASOP, to determine the effectiveness of the articulation and other types of connections between the hull and buoys to the global motion of the ASOP, and to measure the important hydrodynamic parameters for this concept.

All of the model tests were conducted in the deep water wave and towing basin (300 ft long, 50 ft wide and 15 ft deep) at the Offshore Model Basin (OMB) in Escondido, California. The model had a scale of 1:60. In the model test, different configurations and different type of connections between the hull and buoy were tested in various environmental conditions (regular waves, random waves and currents). The test was organized into two phases. The phase I test was conducted in February 1996, and the phase II test was conducted in April, 1996. The following two sections briefly describe the two phases of the model test and the test results. Detailed information about the model construction, test setup and test results can be found in the model test report from OMB, "Model Studies of Articulated Stable Ocean Platform, Preliminary Report No. OMB-95-214-1".

6.2 Phase I Model Test

In the phase I test, the ASOP with a draft of 130 feet and six cylindrical buoys was tested. Figure 6.1 shows the mooring configuration of the ASOP in the phase I test. This configuration was our original design. After the phase I test, we modified the design and increased the draft to 145 ft in order to reduce the motion. In the test, two types of connections between the buoy and hull (hinged connection and spring connection) were tested. The spring connection was used to further de-couple the motion of the buoy from the hull and to reduce interaction forces between the buoys and the hull. Table 6.1 shows the ASOP hydrodynamic configuration. Table 6.4 shows the test matrix of phase I. Table 6.6 shows the environmental condition used in the test. Among the tests, the buoy damage test was designed to investigate the dynamic behavior of the ASOP during a sudden loss of a buoy and the damage stability. A six point mooring system was used for the station-keeping of the ASOP. The fair-leads of the mooring lines were located at the lower corners of the hexagonal hull. The horizontal stiffness of the mooring system is shown in Figure 6.3, together with the modeled mooring stiffness from the model test. Table 6.2 shows the physical properties of the ASOP in the phase I test. At the end of the phase I test, a series of tests were performed for the ASOP with articulated buoys at 145 ft draft. In this series of test, the platform was simply ballasted to the new draft without changes in other configurations. The objective of the test was to see how sensitive the motion of the platform was to the draft change.

The six degree of freedom natural periods were measured by timing free oscillations of the model in still water. The test results are listed as follows:

	Universal joint	Spring connection
Surge	188.0 sec	188.0 sec
Heave	81.0 sec	92.9 sec
Pitch	61.0 sec	83.0 sec

The results of the model test for regular waves are summarized in Table 6.8, and the statistics of the random wave test are listed in Table 6.9. The location of the mooring line #1 and #2, and buoy #1 and #2 are shown in Figure 6.1. The test results shows little difference in the motion of the ASOP between hinged and spring connected buoys, but the heave motion of the ASOP was reduced about 10 percent when the draft was increased to 145 ft. In the random wave tests, strong slow drift motions in surge, heave and pitch were observed. In the 100 year storm wave condition the maximum dynamic tension was six times higher than the mean tension in the mooring line, and the variation of the vertical force at the universal joint was about two times of the pretension.

A large trim angle was observed in the current tests (3.8 degrees in the 4 knots current). Because of the large horizontal spacing among the fair-leads, the asymmetry of the tensions in the mooring lines due to the offset of the ASOP in a current created significant trimming moment and caused the trim.

The buoy damage test showed that the maximum dynamic heeling was about 1.5 larger than the heeling angle at static equilibrium. In the model test, the ASOP did not experience as large a heeling angle as predicted numerically (33 degrees). The numerical analysis was more conservative due to the fact that the contributions of mooring lines to stability was not included in the analysis.

6.3 Phase II Test

In the phase II test, based on the phase I test results that the motion was less at a deeper draft, the draft of ASOP was changed to 145 feet by elongating the center column. The draft of the buoys remained the same as in phase I test. Therefore, the gap between the bottom of the buoys and the hull was increased from 25 to 40 ft. The phase I test also showed that the ASOP experienced large trimming in current due to the moment created by the mooring system. Therefore, in phase II the fair-leads of the mooring line were moved inside to reduce the moment arm. The fair-leads were located on a circle of 60 ft radius at the bottom of the hull. Figure 6.2 shows the general arrangement of the ASOP for the phase II test, and Figure 6.4 shows the target and model test results of the mooring stiffness. In addition to the two types of connection between buoys and hull which were tested in phase I, tests were also performed for the ASOP with buoys which were simply fixed on the hull. The objective was to see the effectiveness of articulation to the motion of the ASOP by comparing with fixed buoys. In phase I, large angular motions of the buoys were observed due to the fact that the natural frequency (pitch and roll) of the buoys was within the wave energy frequency range. To reduce the motion of buoys, a series of buoy tests with water in the buoys' upper compartments were performed. The function of the water in the buoys was: 1) to change the natural frequency of the buoys; and 2) to dissipate energy by creating sloshing in the buoys (damping effects). In the test, seven (7) buoys with different amounts and combinations of water in their upper three compartments were tested in regular and random waves. The configuration which had the best motion overall was chosen to be used in the ASOP tests. Also in phase II, the effects of different buoy shapes on the global motion of the platform were investigated. Four buoy shapes (hourglass shape, inverted cone shape, buoy with link and multi-articulated buoy) were designed in the test. In order to reduce the amount of testing, a buoy test with the four different shaped buoys and the original cylindrical buoys was tested first in regular and random waves. Only the configuration which had the least vertical force on the universal joint was used in the ASOP test. Figure 6.5 shows the configurations of the buoys with different shapes. Their physical properties can be found in the model test report from OMB. In order to further reduce the wave force and motion of the platform, a series of tests were performed for the ASOP which had no center column and the deck was supported by a frame structure. In this configuration, the diameter of the buoys was increased to 39 ft to keep the same water plane area as the original design. Tables 6.2 and 6.3 show the physical properties of the ASOP with the center column and without the center column in phase II test, respectively. Table 6.5 shows the test matrix and Table 6.7 shows the wave conditions in the phase II test.

In the water damped buoy tests, the motion of the buoys varied with wave frequency and the amount of water in the buoy. In general, the buoys with more water inside had larger motion in long waves, and the buoys with less water inside had larger motion in short waves. The buoy, which was filled with 25 percent of water in each of its upper three compartments had less motion in all the wave conditions and was chosen for the damped buoy configuration test of the ASOP.

In the test of buoys with different shapes, the hourglass shaped buoy had the least vertical force at the universal joint in all wave conditions, and was chosen for the optimized buoy configuration test of the ASOP.

The surge, heave and pitch natural periods of the ASOP and the natural period (pitch) of the buoys were measured by timing free oscillations of the model in still water. The test results for fixed, universal joint and spring connections are listed as follows:

	Fixed	Universal joint	Spring connection
Surge	--	212.0 sec	215.0 sec
Heave	--	81.0 sec	96.0 sec
Pitch	67 sec	70.0 sec	116.0 sec
Buoy Pitch	--	14.0 sec	15.7 sec

For the universal joint configuration, the natural periods obtained numerically in Chapter 5 were 214.2, 88.0, 68.2 and 14.1 seconds in surge, heave, pitch and buoy pitch, respectively, and they agreed well with the model tests.

The test results of the ASOP in regular and random waves in phase II are summarized in Tables 6.10 to 6.16. Figures 6.6 to 6.8 show the response amplitude operator of the ASOP obtained from the regular wave tests. The results show that the configuration which had best motion is wave frequency dependent, and there was no one particular configuration which was absolutely better in motion than the rest. Allowing the buoys to move by means of articulation did not have a clear advantage over the fixed buoys. The reason is explained in Chapter 5. In random waves, the wave frequency motions of the ASOP was similar among all the configurations, but the ASOP with fixed buoys showed less slow drift motion than the rest. As explained in Chapter 5, this phenomenon may have been caused by the fact that the large angle rotational motion of the buoys introduced more nonlinear forces into the system and, in turn, created larger drift motions.

In the current test, VIV (vortex induced vibration) was observed when the current speed was over 3 knot. The trimming was greatly reduced due to the change of mooring configuration. In a 4 knot current, the trimming is 1.25 degrees. In the phase I test, the same speed current caused a trim angle of 3.8 degrees.

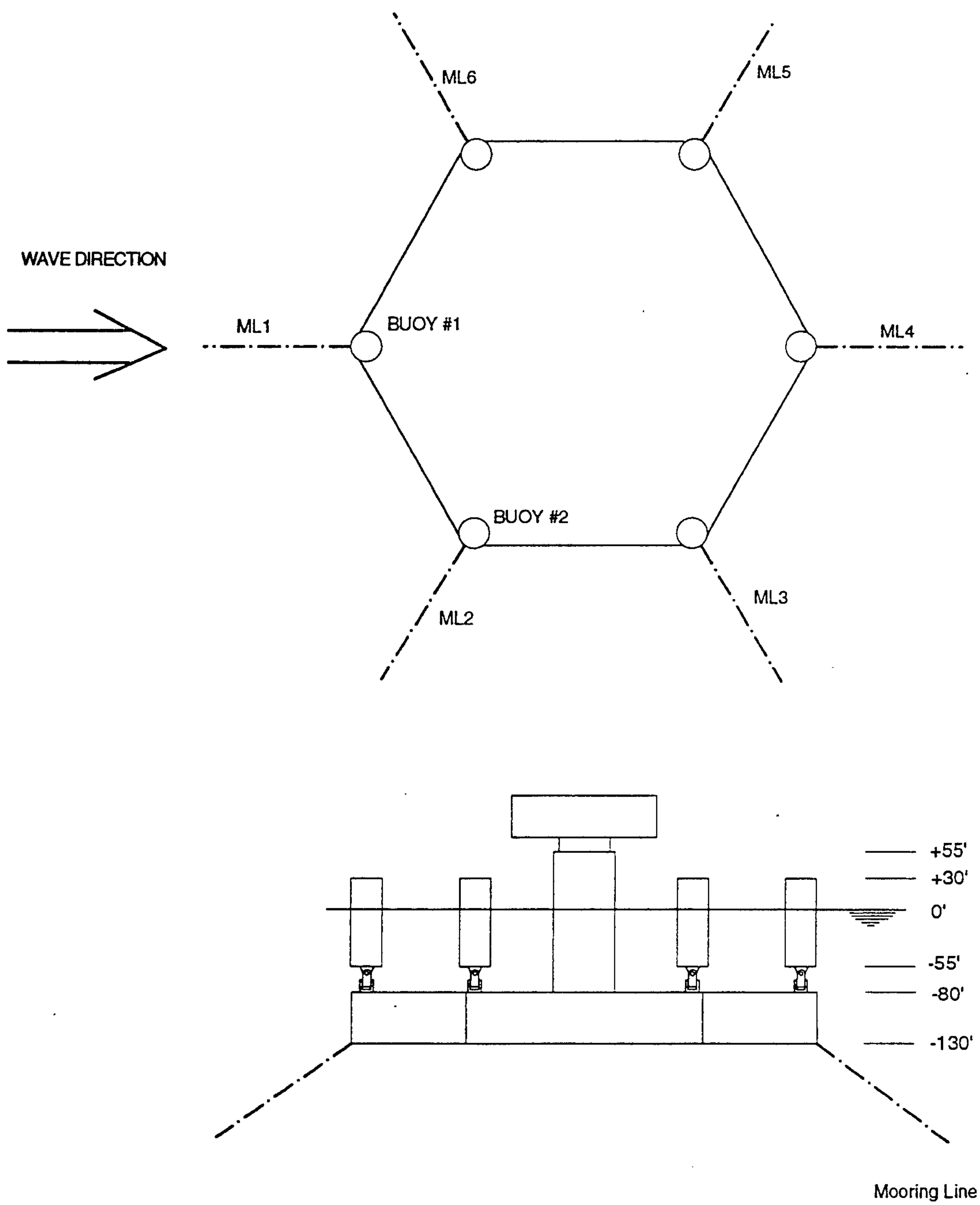


Figure 6.1 The ASOP and mooring configurations in phase I test.

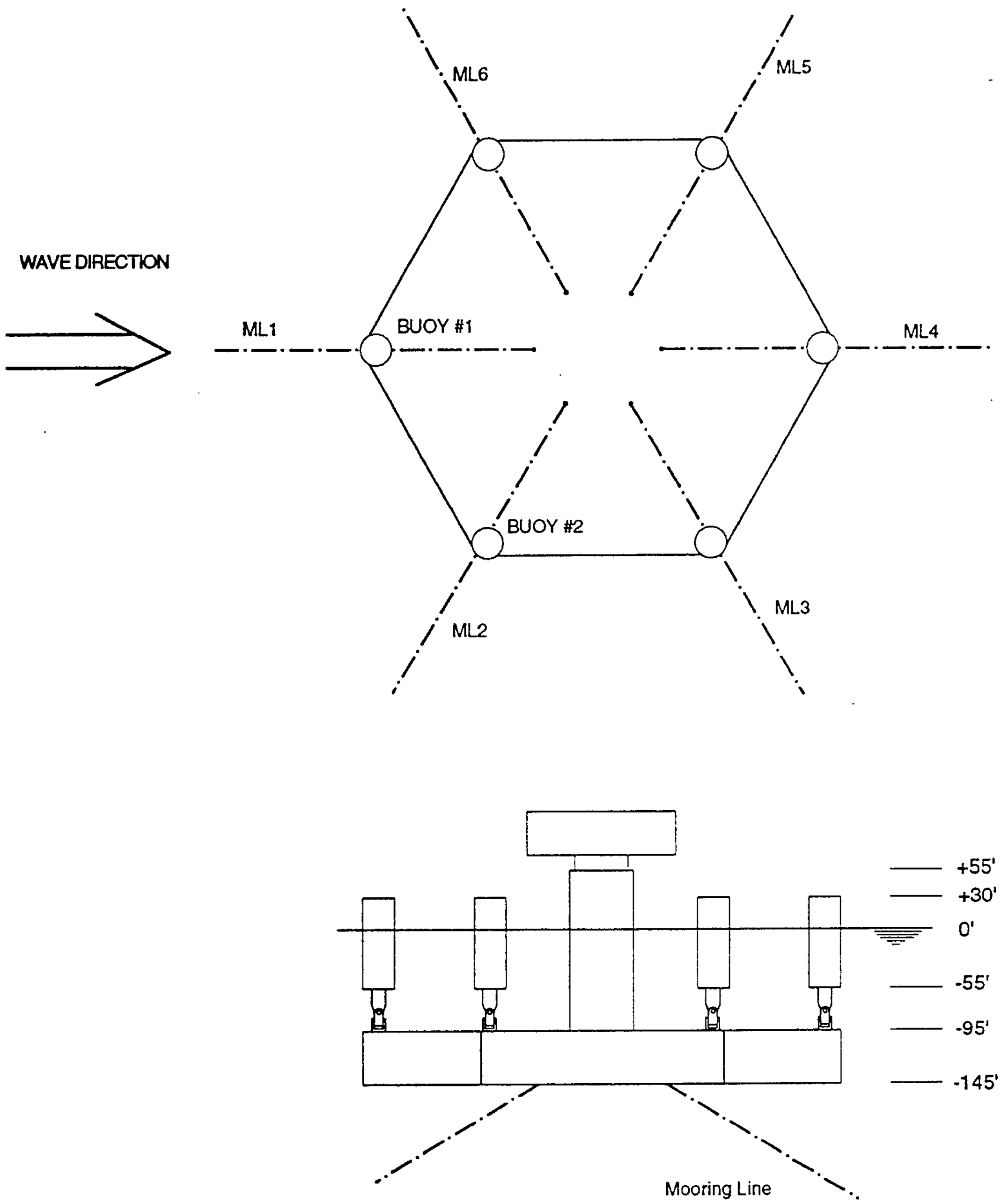


Figure 6.2 The ASOP and mooring configurations in phase II test.

Figure 6.3 Static offset test (surge) in phase I test.

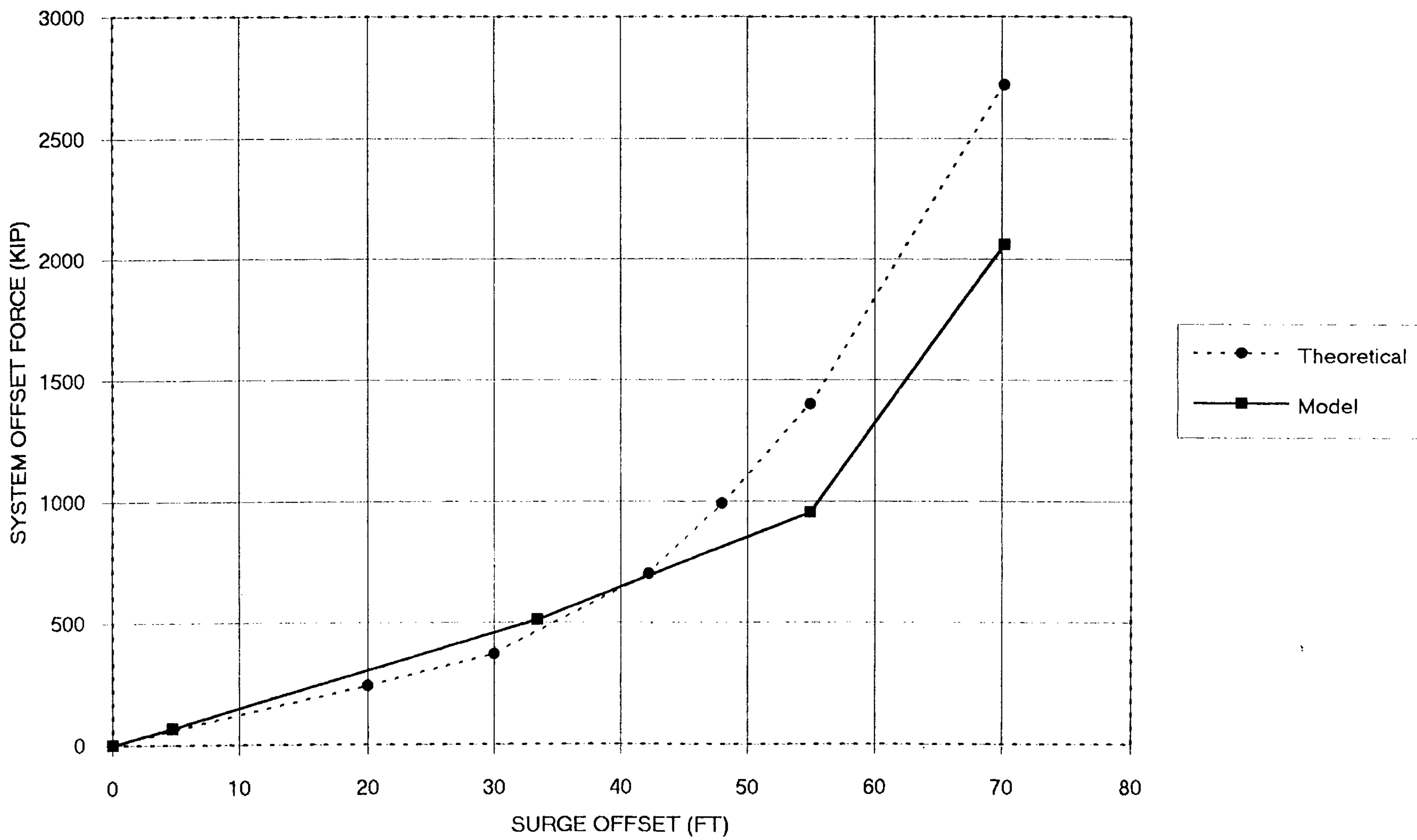
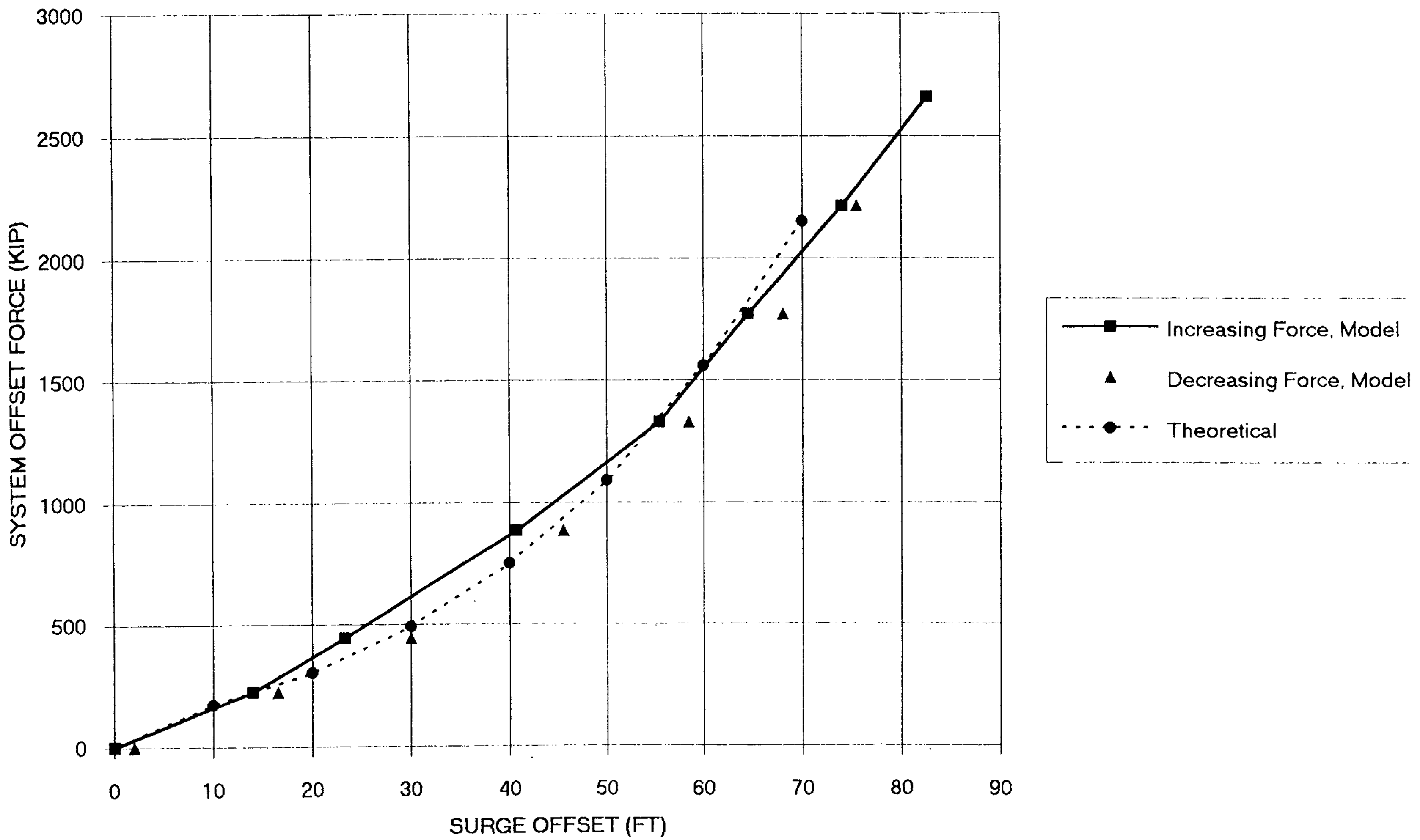


Figure 6.4 Static offset test (surge) in phase II test.



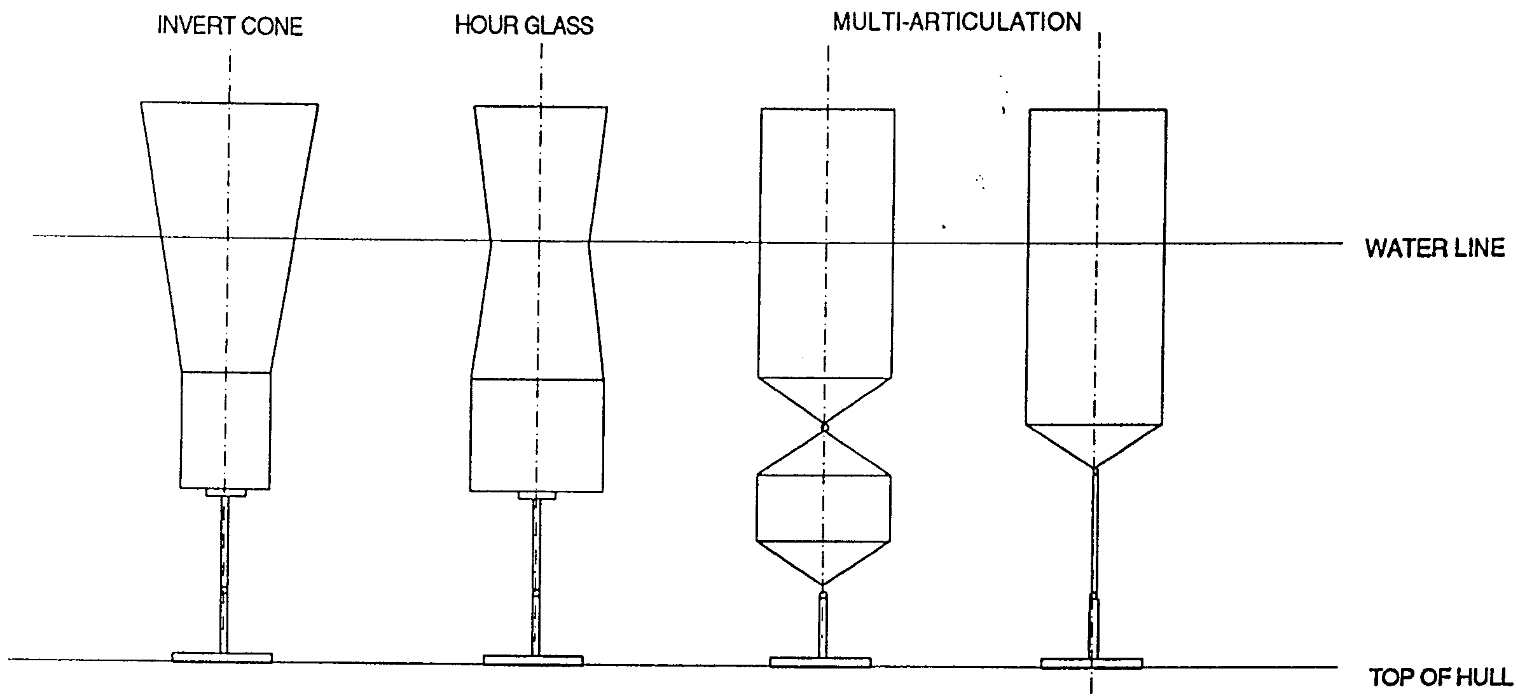


Figure 6.5 Buoy configurations in the buoy test in phase II

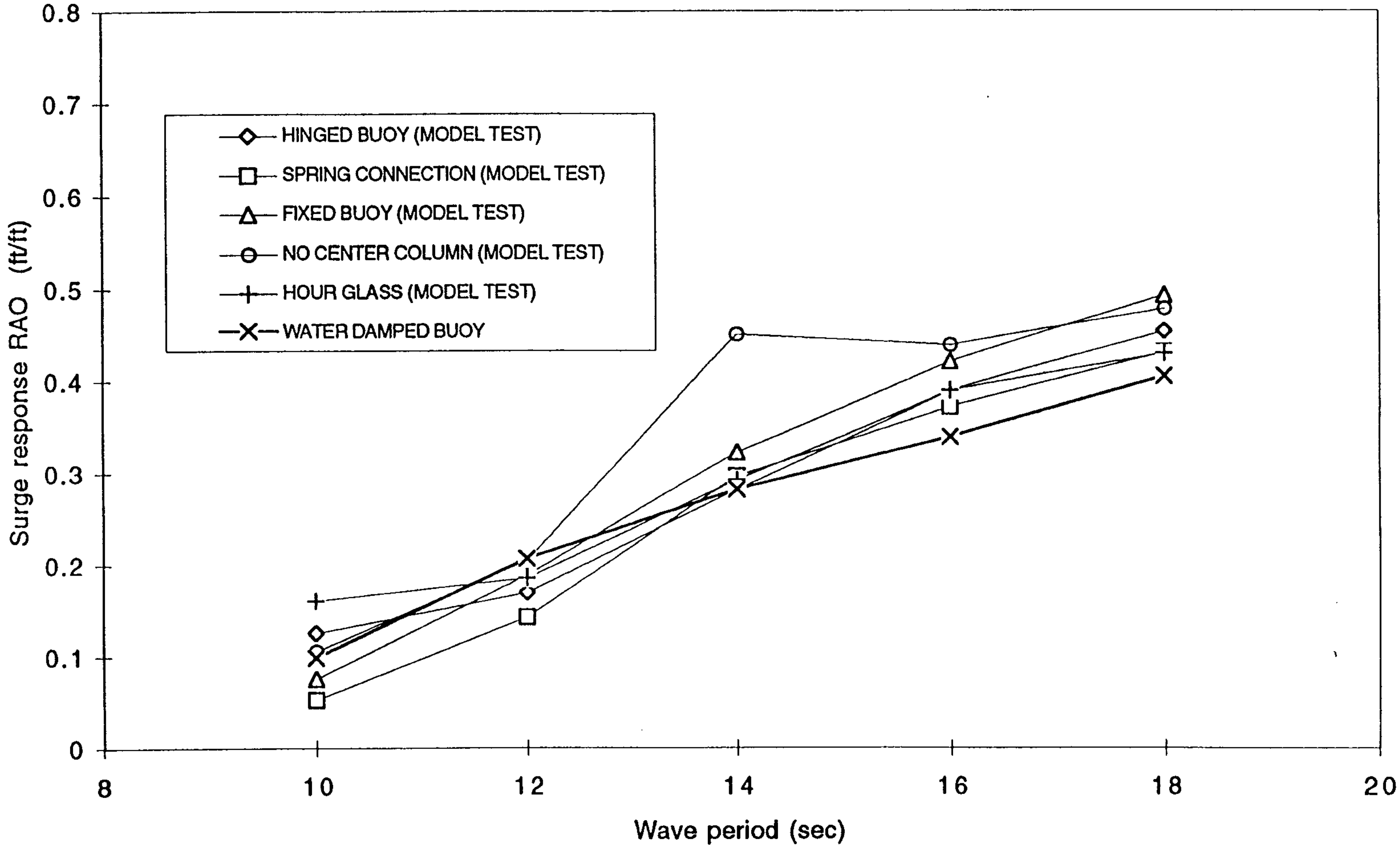


Figure 6.6 Surge response RAO from the regular wave tests.

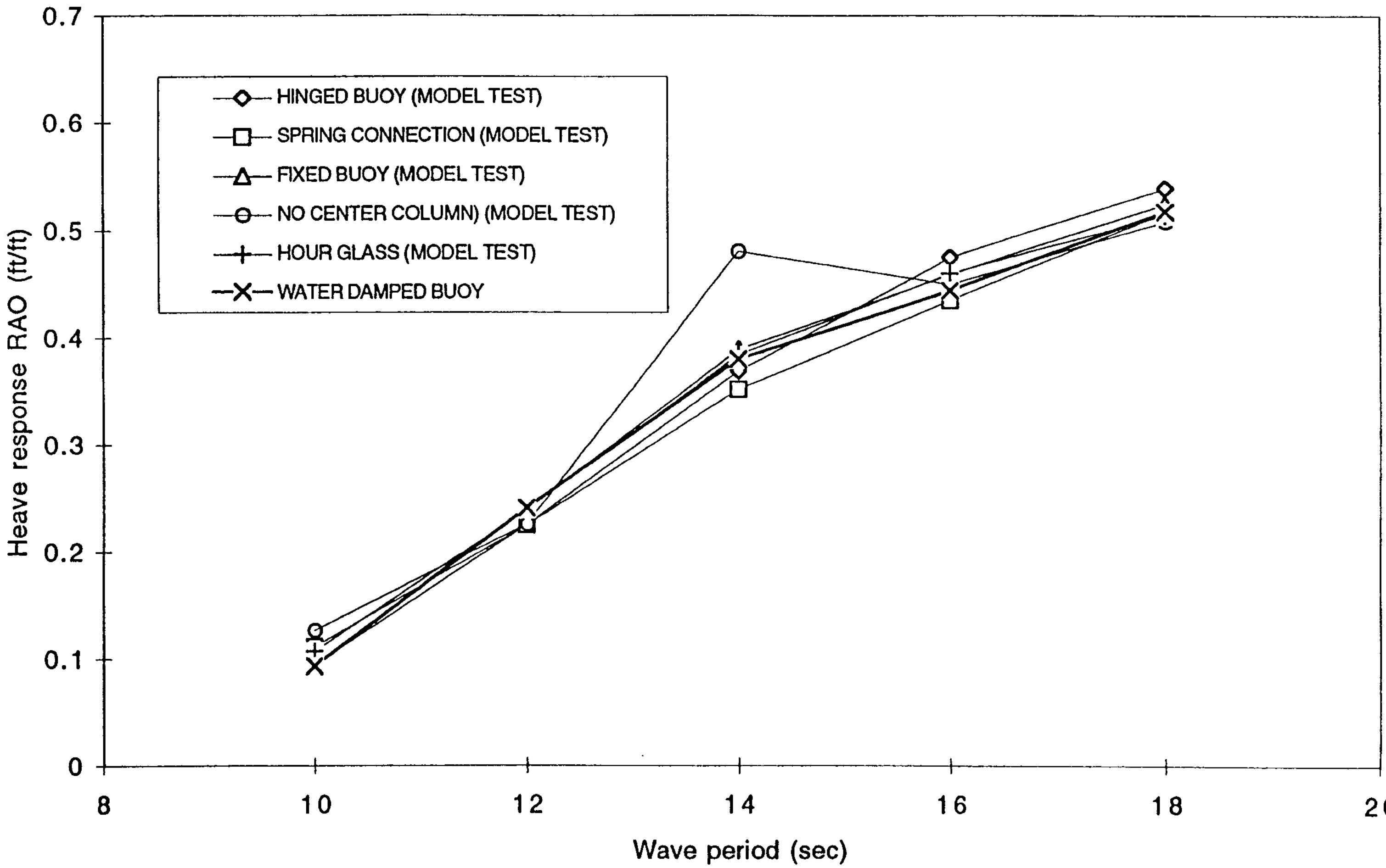


Figure 6.7 Heave response RAO from the regular wave tests.

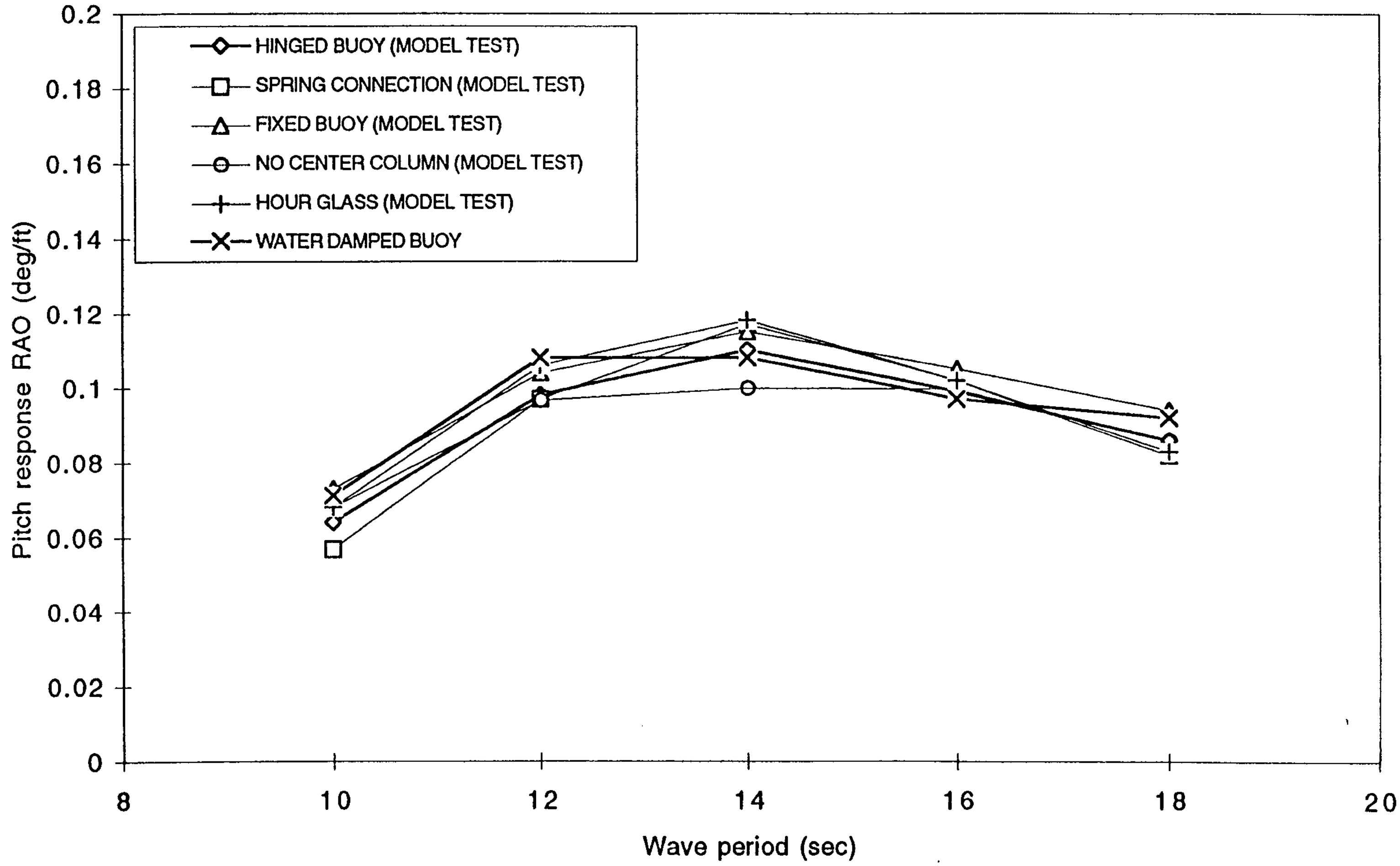


Figure 6.8 Pitch response RAO from the regular wave tests.

Table 6.1 The ASOP configuration in phase I test.

Hull:	
Draft	130 ft
Hull diameter(across corner)	450 ft
Hull height	50 ft
Center Column diameter	60 ft
Center column height	135 ft
Total displacement (with buoys)	450,287 kips
KG	32.41 ft
KB	27.2 ft
Radius of gyration Rxx	107.58 ft
Radius of gyration Ryy	107.58 ft
Radius of gyration Rzz	142 ft
Buoys:	
Buoy diameter	30 ft
Buoy length	85 ft
Buoy draft	55 ft
Buoy weight	850 kips
KG	42.5 ft
Radius of gyration Rxx, Ryy	25.66 ft

Table 6.2 The ASOP configuration in phase II test.

Hull:	
Draft	145 ft
Hull diameter(across corner)	450 ft
Hull height	50 ft
Center Column diameter	60 ft
Center column height	150 ft
Total displacement (with buoys)	452865 kips
KG	33.3 ft
KB	27.8 ft
Radius of gyration Rxx	108.5 ft
Radius of gyration Ryy	108.5 ft
Radius of gyration Rzz	141.8 ft
Buoy:	
Buoy diameter	30 ft
Buoy length	85 ft
Buoy draft	55 ft
Buoy weight	850 kips
KG	42.5 ft
Radius of gyration Rxx, Ryy	25.66 ft

Table 6.3 The ASOP (without center column) configuration in phase II test.

Hull:	
Draft	145 ft
Hull diameter(across corner)	450 ft
Hull height	50 ft
Total displacement (with buoys)	435810 kips
KG	33.2 ft
KB	25 ft
Radius of gyration Rxx	108.5 ft
Radius of gyration Ryy	108.5 ft
Radius of gyration Rzz	141.8 ft
Buoy:	
Buoy diameter	39 ft
Buoy length	85 ft
Buoy draft	55 ft
Buoy weight	1400 kips
KG	42.5 ft
Radius of gyration Rxx, Ryy	27.66 ft

Table 6.4 Test matrix of the phase I test.

Test no.	Type of test	130 ft draft			145 ft draft	Notes
		U joint	Spiing[1]	Spring[2]	U joint	
1	Static offset	x				Calm water
2	Surge free decay	x				Calm water
3	Sway free decay	x				Calm water
4	Heave free decay	x				Calm water
5	Roll free decay	x				Calm water
6	Pitch free decay	x				Calm water
7	Yaw free decay	x				Calm water
8	Regular wave 1	x	x	x	x	
9	Regular wave 2	x	x	x	x	
10	Regular wave 3	x	x	x	x	
11	Irregular wave 1	x	x	x	x	
12	Irregular wave 2	x	x	x	x	
13	Irregular wave 3	x	x	x	x	
14	Current only	x				4 speed towing
15	Buoy damage test	x				Calm water

1. Spring stiffness 30 kips/ft.
2. Spring stiffness 45 kips/ft.

Table 6.5 Test matrix of the phase II test.

No.	Type of test	Buoy test		ASOP with center column					ASOP without center column	
		I[1]	II[2]	U joint	Fixed	Spring	Damped	Optimized	U joint	Fixed
1	Static offset			x						
2	Surge free decay			x	x	x	x	x	x	x
3	Sway free decay			x	x	x	x	x	x	x
4	Heave free decay			x	x	x	x	x	x	x
5	Roll free decay			x	x	x	x	x	x	x
6	Pitch free decay			x	x	x	x	x	x	x
7	Yaw free decay			x	x	x	x	x	x	x
8	Regular wave 1	x	x	x	x	x	x	x	x	x
9	Regular wave 2	x	x	x	x	x	x	x	x	x
10	Regular wave 3	x	x	x	x	x	x	x	x	x
11	Regular wave 4	x	x	x	x	x	x	x	x	x
12	Regular wave 5	x	x	x	x	x	x	x	x	x
13	Irregular wave 1	x	x	x	x	x	x	x	x	x
14	Irregular wave 2	x	x	x	x	x	x	x	x	x
15	Current only			x						

1. A series of buoy tests with different mount of water in the buoys' upper compartments.
2. A series of buoy tests with different buoy shapes (inverted cone, hour glass, multi-articulation, etc.)

Table 6.6 Wave conditions in phase I test.

Wave	Wave height	Wave period	Spectrum	Note
Regular wave 1	12 ft	8.0 sec		
Regular wave 2	20 ft	12.9 sec		
Regular wave 3	20 ft	20.0 sec		
Irregular wave 1	39 ft	14.1 sec	JONSWAP	100 yr. storm
Irregular wave 2	20 ft	11.0 sec	JONSWAP	10 yr. storm
Irregular wave 3	9 ft	8.5 sec	PM	95% non-ex.

Table 6.7 Wave conditions in phase II test.

Wave	Wave height	Wave period	Spectrum	Note
Regular wave 1	12 ft	10.0 sec		
Regular wave 2	12 ft	12.0 sec		
Regular wave 3	20 ft	14.0 sec		
Regular wave 4	20 ft	16.0 sec		
Regular wave 5	20 ft	18.0 sec		
Irregular wave 1	39 ft	14.1 sec	JONSWAP	100 yr. storm
Irregular wave 2	20 ft	11.0 sec	JONSWAP	10 yr. storm

Table 6.8 Summary of the regular wave test results in phase I.

		Hinged buoys, 130 ft draft			Hinged buoys, 145 ft draft			Spring buoy connection, 130 ft draft (spring stiffness = 45kips/ft)		
Wave condition:		Regular 1	Regular 2	Regular 3	Regular 1	Regular 2	Regular 3	Regular 1	Regular 2	Regular 3
Wave Directions	deg	0	0	0	0	0	0	0	0	0
Wave	Ampl.	6.0	10.0	10.0	6.0	10.0	10.0	6.0	10.0	10.0
	Period	8.0	12.9	20.0	8.0	12.9	20.0	8.0	12.9	20.0
Response: (CG)										
Surge (ft)	Amp.	0.269	2.770	6.463	0.297	2.800	6.732	0.382	3.012	6.746
Heave (ft)	Amp.	0.269	2.970	6.449	0.127	2.574	6.067	0.127	2.956	6.435
Pitch (deg)	Amp.	0.113	1.372	0.976	0.009	1.202	0.976	0.113	1.372	1.004
Mooring Tension (kips)										
Line 1	Amp.	4.766	11.143	40.000	3.649	7.877	38.792	3.578	10.069	37.320
Line 2	Amp.	2.136	9.350	25.993	1.768	7.539	23.858	1.768	9.475	27.379
Vertical force on U joint: (kips)										
Buoy 1	Amp.	90.326	134.250	51.393	70.484	132.102	52.722			
Buoy 2	Amp.	43.690	85.714	72.700	37.646	87.469	69.862			

Table 6.9 Statistics of the random wave test results in phase I.

		Hinged buoys, 130 ft draft			Hinged buoys, 145 ft draft			Spring connection, 130 ft draft (spring stiffness = 45kips/ft)		
Wave condition:		100 yr storm	10 yr storm	95% non-ex.	100 yr storm	10 yr storm	95% non-ex.	100 yr storm	10 yr storm	95% non-ex.
Wave	Hs (ft)	39.0	20.0	9.0	39.0	20.0	9.0	39.0	20.0	9.0
(Jonswap)	Tp (sec)	14.1	11.0	8.5	14.1	11.0	8.5	14.1	11.0	8.5
	Gamma	2.0	2.0	1.0	2.0	2.0	1.0	2.0	2.0	1.0
Wave: (ft)	mean	0.323	0.437	0.405	0.345	0.422	0.314	0.395	0.449	
(measured)	rms	12.078	5.700	2.438	12.139	5.716	2.524	12.509	5.695	
	max	49.449	26.050	9.578	49.306	23.964	9.602	50.678	28.882	
	min	-47.744	-16.879	-9.149	-45.531	-16.939	-9.453	-44.324	-17.934	
Response: (CG)										
Surge (ft)	mean	-20.758	-6.155	-0.698	-17.689	-10.024	-1.856	-17.515	-6.030	
	rms	15.770	7.926	1.448	14.350	9.282	3.630	15.980	6.110	
	rms (low)	15.310	7.900	1.420	13.900	9.220	3.620	15.530	6.040	
	rms(high)	3.760	0.970	0.310	3.570	1.070	0.300	3.740	0.920	
	max	22.385	16.430	3.606	24.284	14.501	5.951	26.007	14.501	
	min	-66.522	-27.695	-5.151	-58.577	-37.686	-9.404	-78.451	-37.686	
Heave (ft)	mean	2.387	1.348	0.321	1.023	0.670	0.223	3.452	1.570	
	rms	6.230	3.986	1.419	4.970	2.556	1.020	5.910	3.600	
	rms (low)	4.940	3.790	1.410	3.530	2.430	1.000	4.470	3.480	
	rms(high)	3.800	0.900	0.230	3.490	0.800	0.210	3.880	0.930	
	max	30.631	14.645	4.072	21.683	9.690	3.349	33.758	9.690	
	min	-14.328	-9.715	-3.741	-18.358	-6.250	-2.477	-12.428	-6.250	
Pitch (deg)	mean	-0.035	-0.037	-0.027	-0.038	0.059	0.005	-1.458	-0.140	
	rms	1.940	1.190	0.419	1.690	0.888	0.360	2.400	1.260	
	rms (low)	1.400	1.050	0.400	1.210	0.780	0.340	1.990	1.140	
	rms(high)	1.340	0.520	0.140	1.170	0.430	0.100	1.340	0.540	
	max	5.847	3.811	1.184	5.355	2.870	1.210	4.123	2.870	
	min	-8.890	-4.174	-1.288	-7.939	-2.961	-1.288	-11.546	-2.961	
Mooring Tension: (kips)										
Line 1	mean	300.967	215.167	175.420	406.641	333.037	271.975	506.058	338.260	
	rms	125.690	52.500	13.778	134.550	60.606	22.980	205.780	41.400	
	rms (low)	120.470	52.170	13.450	126.370	60.240	22.830	193.450	40.940	
	rms(high)	35.830	5.950	2.670	46.200	6.320	2.630	70.150	6.190	
	max	1665.293	370.234	224.914	1798.618	524.930	332.594	2818.098	524.930	
	min	32.579	92.417	143.706	144.533	183.000	221.467	266.447	183.000	
Line 2	mean	310.146	257.650	235.632	332.705	302.214	277.265	270.428	227.350	
	rms	60.480	27.460	7.105	45.550	27.976	10.700	83.080	23.010	
	rms (low)	57.540	27.260	6.990	43.420	27.780	10.600	76.270	22.730	
	rms(high)	18.650	3.360	1.480	13.770	3.270	1.460	32.940	3.610	
	max	876.646	330.599	256.307	593.327	385.310	303.588	1270.393	385.310	
	min	159.728	189.445	215.447	210.723	233.011	251.584	118.867	233.011	
Vertical force on U joint: (kips)										
Buoy 1	mean	8.829	16.231	-0.264	-20.234	13.187	3.981			
	rms	315.340	208.790	91.718	264.640	165.491	72.520			
	rms (low)	286.620	191.430	85.510	238.380	151.860	67.280			
	rms(high)	131.490	83.360	34.870	114.940	66.120	27.060			
	max	935.658	708.081	276.372	799.476	484.922	196.950			
	min	-1439.129	-823.372	292.749	-1285.576	-627.451	-206.608			
Buoy 2	mean	-44.616	553.462	41.329	-31.554	-3.826	0.133			
	rms	230.440	311.700	113.762	186.370	118.481	49.499			
	rms (low)	209.830	305.270	114.820	165.240	109.330	46.760			
	rms(high)	95.270	63.010	110.890	86.190	45.920	18.210			
	max	595.225	987.807	840.535	500.475	331.355	155.724			
	min	-971.621	-407.828	-202.300	-864.030	-415.750	-124.441			

Table 6.10 Statistics of the test results in regular wave (wave height=15ft, period=10sec)

REGULAR WAVE: H=15 FT, T=10 SEC							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.32	0.27	0.18	0.40	0.17	0.11
	MAX.	8.05	8.11	8.28	8.46	7.68	8.42
	MIN.	-7.45	-8.96	-8.49	-8.32	-9.21	-9.75
	RMS	5.13	5.46	5.50	5.43	5.57	4.97
SURGE: (FT)							
	MEAN	9.81	-3.62	0.68	-15.71	-6.96	-6.04
	MAX.	24.00	5.64	5.06	5.43	-2.11	22.27
	MIN.	-3.98	-12.22	-2.72	-37.90	-11.51	-31.52
	RMS	9.30	5.66	1.74	12.34	2.89	16.59
	RMS(L)	9.27	5.65	1.65	12.30	2.88	16.58
	RMS(H)	0.64	0.41	0.54	0.87	0.29	0.52
	RAO	0.125	0.075	0.098	0.160	0.052	
HEAVE: (FT)							
	MEAN	1.74	0.71	0.76	1.75	0.81	1.19
	MAX.	4.55	2.59	3.16	4.56	2.99	4.75
	MIN.	-1.01	-1.13	-1.89	-0.57	-1.27	-1.06
	RMS	1.14	0.85	1.00	1.13	0.88	1.18
	RMS(L)	1.04	0.68	0.85	0.97	0.62	1.00
	RMS(H)	0.48	0.52	0.51	0.58	0.62	0.63
	RAO	0.094	0.095	0.093	0.107	0.111	
PITCH: DEG)							
	MEAN	-0.05	0.06	-0.02	0.01	-0.34	-0.02
	MAX.	1.24	0.94	1.03	1.15	0.40	2.50
	MIN.	-1.42	-0.71	-0.82	-1.50	-1.10	-2.72
	RMS	0.61	0.42	0.42	0.48	0.34	0.91
	RMS(L)	0.51	0.13	0.15	0.30	0.11	0.84
	RMS(H)	0.33	0.40	0.39	0.37	0.32	0.34
	RAO	0.064	0.073	0.071	0.068	0.057	
JOINT 1 TSN: (KIPS)							
	MEAN	1879.24		1477.93	1685.82	1666.76	
	MAX.	2194.35		1708.03	1883.11	1805.30	
	MIN.	1521.03		1221.71	1470.70	1560.19	
	RMS	114.58		116.81	62.52	60.36	
	RMS(L)	98.61		41.39	42.63	14.37	
	RMS(H)	105.73		109.24	45.74	85.63	
	RAO	20.610	0.000	19.862	8.424	15.373	
JOINT 2 TSN: (KIPS)							
	MEAN	1837.60		1425.06	1583.82	1671.63	
	MAX.	2070.98		1606.83	1710.74	1780.02	
	MIN.	1596.43		1229.27	1444.03	1596.43	
	RMS	104.95		91.85	45.06	43.98	
	RMS(L)	72.78		38.86	39.49	12.83	
	RMS(H)	75.61		83.23	21.71	42.06	
	RAO	14.739	0.000	15.133	3.998	7.551	
MOOR 1 TSN: (KIPS)							
	MEAN	325.81	282.53	317.87	313.98	291.53	288.74
	MAX.	413.91	329.67	340.65	498.16	322.34	472.52
	MIN.	241.75	234.43	285.71	201.46	260.07	146.52
	RMS	53.72	27.33	11.65	75.00	16.64	89.73
	RMS(L)	53.53	27.12	11.02	74.68	16.30	89.61
	RMS(H)	4.54	3.44	3.77	6.90	3.36	4.50
	RAO	0.885	0.630	0.685	1.271	0.603	

Table 6.11 Statistics of the test results in regular wave (wave height=15ft, period=12sec)

REGULAR WAVE: H=15 FT, T=12 SEC							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.26	0.17	0.15	0.07	0.01	0.20
	MAX.	8.35	8.54	7.92	7.52	7.98	8.09
	MIN.	-9.57	-8.66	-9.03	-8.77	-10.12	-8.92
	RMS	5.63	5.84	5.73	5.45	5.78	5.48
SURGE: (FT)							
	MEAN	-7.36	-7.16	0.85	5.83	-1.34	-4.03
	MAX.	-0.98	3.08	4.08	19.02	1.86	8.07
	MIN.	-14.69	-17.12	-5.36	-8.06	-6.02	-17.99
	RMS	3.17	5.81	1.94	6.67	1.64	7.16
	RMS(L)	3.03	5.71	1.54	6.68	1.42	7.07
	RMS(H)	0.95	1.10	1.18	1.01	0.82	1.12
	RAO	0.169	0.188	0.206	0.185	0.142	
HEAVE: (FT)							
	MEAN	1.24	0.52	1.01	1.11	0.58	2.01
	MAX.	4.70	3.32	4.28	4.59	3.77	5.55
	MIN.	-2.17	-2.27	-2.30	-2.12	-1.90	-0.78
	RMS	1.51	1.45	1.50	1.56	1.41	1.50
	RMS(L)	0.82	0.38	0.59	0.84	0.55	0.85
	RMS(H)	1.27	1.40	1.38	1.31	1.30	1.24
	RAO	0.226	0.240	0.241	0.240	0.225	
PITCH: DEG)							
	MEAN	-0.08	0.01	0.26	-0.20	-0.14	-0.10
	MAX.	1.32	1.08	1.76	1.33	1.06	1.03
	MIN.	-1.42	-1.07	-1.10	-1.78	-1.48	-1.22
	RMS	0.59	0.62	0.67	0.69	0.58	0.53
	RMS(L)	0.23	0.07	0.25	0.37	0.17	0.08
	RMS(H)	0.55	0.61	0.62	0.58	0.56	0.53
	RAO	0.098	0.104	0.108	0.106	0.097	
JOINT 1 TSN: (KIPS)							
	MEAN	1897.77		1520.97	1687.64	1637.01	
	MAX.	2120.43		1723.59	1871.44	1801.40	
	MIN.	1630.22		1252.83	1517.39	1536.84	
	RMS	109.92		116.03	64.08	60.45	
	RMS(L)	30.52		38.35	44.08	16.75	
	RMS(H)	105.60		109.51	46.52	58.09	
	RAO	18.757	0.000	19.112	8.536	10.050	
JOINT 2 TSN: (KIPS)							
	MEAN	1861.13		1456.70	1601.04	1646.79	
	MAX.	2050.19		1641.46	1741.92	1780.02	
	MIN.	1665.71		1246.59	1475.20	1558.33	
	RMS	91.74		88.70	50.60	48.18	
	RMS(L)	29.51		29.41	34.41	11.67	
	RMS(H)	86.86		83.68	37.10	46.74	
	RAO	15.428	0.000	14.604	6.807	8.087	
MOOR 1 TSN: (KIPS)							
	MEAN	342.84	278.56	314.48	311.42	294.50	300.90
	MAX.	391.93	336.99	344.32	391.93	329.67	377.28
	MIN.	296.70	223.44	278.38	230.76	271.06	238.09
	RMS	19.69	28.36	13.18	39.76	11.65	35.00
	RMS(L)	17.66	26.85	9.85	38.85	8.73	34.29
	RMS(H)	8.71	9.12	8.76	8.48	7.71	7.01
	RAO	1.547	1.562	1.529	1.556	1.334	

Table 6.12 Statistics of the test results in regular wave (wave height=20ft, period=14sec)

REGULAR WAVE: H=20 FT, T=14 SEC							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.19	0.11	0.10	0.06	0.03	0.03
	MAX.	12.45	12.38	12.89	12.72	12.40	8.24
	MIN.	-13.89	-12.75	-12.97	-12.60	-12.61	-9.56
	RMS	8.03	8.02	8.03	7.71	8.12	6.20
SURGE: (FT)							
	MEAN	-9.03	-2.09	-2.86	-1.21	-6.60	-3.36
	MAX.	1.00	5.29	3.14	5.76	0.82	8.72
	MIN.	-18.11	-9.98	-8.92	-9.00	-14.23	-12.75
	RMS	3.74	3.40	2.63	3.24	3.14	4.64
	RMS(L)	2.97	2.21	1.35	2.34	2.02	3.70
	RMS(H)	2.26	2.58	2.26	2.25	2.40	2.79
	RAO	0.281	0.322	0.281	0.292	0.296	
HEAVE: (FT)							
	MEAN	1.20	0.46	1.98	1.17	1.11	0.72
	MAX.	6.91	5.99	9.70	7.16	6.70	5.55
	MIN.	-4.36	-4.75	-5.20	-4.56	-3.90	-4.24
	RMS	3.06	3.16	3.47	3.06	2.92	2.99
	RMS(L)	0.81	0.54	1.66	0.76	0.55	0.28
	RMS(H)	2.96	3.12	3.05	2.96	2.86	2.98
	RAO	0.369	0.389	0.380	0.384	0.352	
PITCH: DEG)							
	MEAN	-0.21	-0.04	-0.11	-0.71	-0.81	-0.09
	MAX.	1.41	1.36	5.17	1.13	0.90	1.10
	MIN.	-1.80	-1.45	-5.66	-2.49	-2.71	-1.26
	RMS	0.89	0.92	2.54	0.94	0.96	0.62
	RMS(L)	0.13	0.06	2.39	0.23	0.17	0.06
	RMS(H)	0.88	0.92	0.87	0.91	0.95	0.62
	RAO	0.110	0.115	0.108	0.118	0.117	
JOINT 1 TSN: (KIPS)							
	MEAN	1866.98		1544.15	1659.70	1646.74	
	MAX.	2139.88		2396.66	1859.76	1883.11	
	MIN.	1579.64		443.59	1509.61	1521.28	
	RMS	123.91		403.81	72.43	97.54	
	RMS(L)	34.46		377.28	25.24	14.20	
	RMS(H)	119.02		143.97	67.89	96.50	
	RAO	14.822	0.000	17.929	8.805	11.884	
JOINT 2 TSN: (KIPS)							
	MEAN	1852.62		1448.82	1574.08	1632.75	
	MAX.	2105.61		2226.85	1721.13	1814.66	
	MIN.	1662.25		602.32	1444.03	1478.66	
	RMS	117.10		320.03	62.26	76.68	
	RMS(L)	31.07		293.60	20.22	12.80	
	RMS(H)	112.90		127.34	58.88	75.60	
	RAO	14.060	0.000	15.858	7.637	9.310	
MOOR 1 TSN: (KIPS)							
	MEAN	364.23	281.71	330.58	325.19	323.82	288.36
	MAX.	443.22	329.67	377.28	369.96	373.62	340.65
	MIN.	307.69	238.09	285.71	278.38	271.06	219.78
	RMS	24.71	21.29	20.66	21.70	21.56	25.07
	RMS(L)	15.61	10.11	8.87	12.14	12.73	16.79
	RMS(H)	19.15	18.74	18.66	17.99	17.40	18.62
	RAO	2.385	2.337	2.324	2.333	2.143	

Table 6.13 Statistics of the test results in regular wave (wave height=20ft, period=16sec)

REGULAR WAVE: H=20 FT, T=16 SEC							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.18	0.10	0.11	0.14	-0.05	-0.01
	MAX.	13.86	13.03	13.20	12.60	13.19	12.88
	MIN.	-13.33	-13.55	-14.72	-12.53	-13.22	-14.85
	RMS	8.32	8.48	8.59	8.32	8.63	8.43
SURGE: (FT)							
	MEAN	-5.17	-3.67	-4.07	-1.28	-6.83	-9.54
	MAX.	1.29	7.82	4.70	5.14	-1.03	3.70
	MIN.	-11.68	-11.58	-12.52	-7.86	-13.44	-19.76
	RMS	3.38	4.40	3.57	3.36	3.33	4.81
	RMS(L)	0.99	2.59	2.08	0.91	0.88	3.07
	RMS(H)	3.24	3.56	2.91	3.24	3.21	3.70
	RAO	0.389	0.420	0.339	0.389	0.372	
HEAVE: (FT)							
	MEAN	0.56	0.41	2.33	0.54	0.40	1.05
	MAX.	6.95	6.80	11.43	6.85	6.88	7.21
	MIN.	-5.89	-5.67	-6.44	-5.41	-5.28	-4.89
	RMS	3.97	3.90	4.15	3.85	3.75	3.80
	RMS(L)	0.41	0.30	1.64	0.33	0.23	0.32
	RMS(H)	3.95	3.89	3.81	3.83	3.75	3.79
	RAO	0.475	0.459	0.444	0.460	0.435	
PITCH: DEG)							
	MEAN	-0.19	-0.01	-0.12	-0.66	-0.75	-0.09
	MAX.	1.21	1.37	5.68	1.06	0.86	1.38
	MIN.	-1.64	-1.41	-6.25	-2.13	-2.35	-1.60
	RMS	0.82	0.89	3.18	0.86	0.89	0.84
	RMS(L)	0.08	0.06	3.07	0.15	0.14	0.05
	RMS(H)	0.82	0.89	0.83	0.85	0.88	0.84
	RAO	0.099	0.105	0.097	0.102	0.102	
JOINT 1 TSN: (KIPS)							
	MEAN	1869.19		1567.70	1650.78	1662.90	
	MAX.	2069.85		2431.68	1754.72	1844.20	
	MIN.	1735.26		575.87	1529.06	1540.74	
	RMS	100.75		430.45	52.18	72.52	
	RMS(L)	18.05		408.16	9.79	13.67	
	RMS(H)	99.12		136.71	51.25	71.22	
	RAO	11.913	0.000	15.915	6.160	8.253	
JOINT 2 TSN: (KIPS)							
	MEAN	1847.41		1475.51	1573.77	1638.78	
	MAX.	2032.88		2164.50	1672.64	1762.70	
	MIN.	1658.78		681.99	1447.49	1471.74	
	RMS	103.43		331.68	59.17	64.39	
	RMS(L)	16.88		307.65	11.62	13.30	
	RMS(H)	102.04		123.97	58.01	63.01	
	RAO	12.264	0.000	14.432	6.972	7.301	
MOOR 1 TSN: (KIPS)							
	MEAN	336.00	281.54	335.42	307.36	310.00	315.75
	MAX.	384.61	333.33	391.93	355.30	358.97	373.62
	MIN.	289.37	219.78	271.06	256.41	271.06	245.42
	RMS	26.46	26.82	25.92	25.08	23.62	28.39
	RMS(L)	6.80	11.25	11.42	6.13	6.28	14.74
	RMS(H)	25.57	24.34	23.28	24.32	22.77	24.26
	RAO	3.073	2.870	2.710	2.923	2.638	

Table 6.14 Statistics of the test results in regular wave (wave height=20ft, period=18sec)

REGULAR WAVE: H=20 FT, T=18 SEC							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.06	0.03	-0.03	0.05	-0.09	-0.14
	MAX.	11.92	11.70	11.54	12.54	11.15	11.56
	MIN.	-12.73	-13.25	-12.68	-13.26	-12.59	-13.93
	RMS	8.46	8.34	8.37	8.39	8.53	8.60
SURGE: (FT)							
	MEAN	2.43	2.63	-3.00	-1.23	-3.00	-1.66
	MAX.	16.92	16.47	3.42	6.30	6.54	7.89
	MIN.	-9.74	-9.74	-9.03	-7.05	-9.41	-12.35
	RMS	5.83	6.08	3.46	3.67	3.93	4.49
	RMS(L)	4.39	4.49	0.70	0.68	1.41	1.79
	RMS(H)	3.83	4.11	3.38	3.60	3.67	4.11
	RAO	0.453	0.493	0.404	0.429	0.430	
HEAVE: (FT)							
	MEAN	0.41	0.29	2.34	0.49	0.44	0.30
	MAX.	7.49	7.18	10.06	7.65	7.47	7.57
	MIN.	-6.75	-6.47	-5.18	-5.99	-6.09	-6.51
	RMS	4.57	4.37	4.43	4.32	4.40	4.38
	RMS(L)	0.31	0.19	0.93	0.28	0.20	0.27
	RMS(H)	4.56	4.37	4.33	4.31	4.40	4.37
	RAO	0.539	0.524	0.517	0.514	0.516	
PITCH: DEG)							
	MEAN	0.06	-0.07	-0.07	-0.01	-0.14	0.02
	MAX.	1.31	1.25	1.70	1.33	1.22	1.41
	MIN.	-1.13	-1.33	-1.61	-1.23	-1.44	-1.31
	RMS	0.74	0.78	0.81	0.71	0.71	0.75
	RMS(L)	0.06	0.04	0.26	0.08	0.10	0.05
	RMS(H)	0.73	0.78	0.77	0.70	0.70	0.74
	RAO	0.086	0.094	0.092	0.083	0.082	
JOINT 1 TSN: (KIPS)							
	MEAN	1881.15		1562.47	1676.31	1628.43	
	MAX.	1992.04		1766.39	1743.05	1715.81	
	MIN.	1750.83		1307.30	1599.09	1548.52	
	RMS	65.17		89.08	34.19	40.74	
	RMS(L)	11.43		33.84	8.43	9.99	
	RMS(H)	64.16		82.40	33.14	39.50	
	RAO	7.584	0.000	9.845	3.950	4.631	
JOINT 2 TSN: (KIPS)							
	MEAN	1852.35		1480.16	1587.60	1640.42	
	MAX.	1998.24		1710.74	1669.17	1752.31	
	MIN.	1696.89		1205.02	1520.23	1551.41	
	RMS	82.94		109.04	36.29	53.24	
	RMS(L)	12.00		37.70	8.81	8.72	
	RMS(H)	82.07		102.30	35.21	52.52	
	RAO	9.701	0.000	12.222	4.197	6.157	
MOOR 1 TSN: (KIPS)							
	MEAN	312.12	276.28	330.36	294.98	287.64	271.06
	MAX.	395.60	347.98	377.28	340.65	336.99	329.67
	MIN.	223.44	201.46	278.38	241.75	223.44	208.79
	RMS	40.27	33.76	26.39	28.96	28.75	29.48
	RMS(L)	27.53	20.28	5.83	4.51	8.02	8.59
	RMS(H)	29.39	26.99	25.73	28.61	27.61	28.20
	RAO	3.474	3.236	3.074	3.410	3.237	

Table 6.15 Statistics of the test results in 10 year storm (Hs=20ft, Tp=11sec, JONSWAP spectrum, over-shooting parameter=2)

IRREGULAR WAVE: Hs=20 FT, Tp=11 SEC, JONSWAP (GAMMA=2)							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	0.33	0.29	0.25	-0.12	0.21	0.24
	MAX.	26.65	22.86	23.90	22.29	21.69	19.92
	MIN.	-18.65	-19.89	-17.58	-20.52	-18.76	-16.59
	RMS	5.57	5.52	5.52	5.40	5.49	5.23
SURGE: (FT)							
	MEAN	-6.16	-2.58	-3.22	-12.17	-4.62	-9.48
	MAX.	15.68	15.19	12.19	8.30	19.39	15.84
	MIN.	-34.96	-18.52	-19.20	-35.21	-30.65	-42.40
	RMS	8.37	6.18	5.39	7.90	8.16	10.40
	RMS(L)	8.32	6.12	5.33	7.86	8.12	10.35
	RMS(H)	0.84	0.82	0.78	0.87	0.74	0.97
HEAVE: (FT)							
	MEAN	1.09	0.33	0.75	0.83	0.96	1.26
	MAX.	13.68	10.24	11.95	12.22	10.65	14.75
	MIN.	-9.26	-7.22	-8.15	-9.71	-6.61	-8.84
	RMS	4.04	2.82	3.39	4.30	3.08	3.93
	RMS(L)	3.93	2.63	3.24	4.19	2.92	3.81
	RMS(H)	0.96	1.02	0.99	0.94	1.00	0.95
PITCH: DEG)							
	MEAN	-0.06	-0.11	0.05	-0.10	-0.40	
	MAX.	3.55	2.17	3.27	3.31	2.48	
	MIN.	-3.64	-2.44	-3.19	-4.29	-3.98	
	RMS	1.36	0.73	1.10	1.18	1.02	
	RMS(L)	1.29	0.58	1.02	1.10	0.92	
	RMS(H)	0.44	0.44	0.42	0.43	0.42	
JOINT 1 TSN: (KIPS)							
	MEAN	1871.24		1498.54	1666.66	1656.25	
	MAX.	2626.21		2182.68	2314.96	2116.54	
	MIN.	1132.22		665.36	929.91	1233.38	
	RMS	255.59		222.31	216.38	140.20	
	RMS(L)	232.16		196.13	209.53	121.51	
	RMS(H)	106.89		104.66	54.03	69.94	
JOINT 2 TSN: (KIPS)							
	MEAN	1846.19		1416.25	1566.65	1645.38	
	MAX.	2472.78		1946.28	2098.69	2012.09	
	MIN.	1256.98		799.76	976.41	1274.30	
	RMS	196.26		175.54	187.46	110.16	
	RMS(L)	177.28		153.12	182.54	96.55	
	RMS(H)	84.22		85.85	42.68	53.04	
MOOR 1 TSN: (KIPS)							
	MEAN	354.42	300.00	326.30	322.04	297.25	311.19
	MAX.	743.58	391.93	428.56	512.81	545.78	677.64
	MIN.	216.11	212.45	241.75	186.81	164.83	164.83
	RMS	65.36	32.31	32.16	48.94	50.15	69.42
	RMS(L)	64.64	31.66	31.52	48.27	49.69	69.03
	RMS(H)	9.69	6.45	6.39	8.02	6.78	7.34

Table 6.16 Statistics of the test results in 100 year storm (Hs=39ft, Tp=14.1sec, JONSWAP spectrum, over-shooting parameter=2)

IRREGULAR WAVE: Hs=39 FT, Tp=14.1 SEC, JONSWAP (GAMMA=2)							
		U JOINT	FIXED	DAMPED	HOUR GLASS	SPRING CONN.	WITHOUT C.C
WAVE ELEV. 2: (FT)							
	MEAN	-0.08	-0.05	-0.07	-0.31	-0.20	-0.13
	MAX.	46.64	51.07	48.74	48.59	45.47	48.41
	MIN.	-41.59	-41.28	-40.34	-42.15	-41.68	-40.00
	RMS	10.82	10.73	10.73	10.90	10.96	11.11
SURGE: (FT)							
	MEAN	-17.70	-11.62	-12.12	-17.59	-19.56	-16.03
	MAX.	29.99	25.49	33.52	29.86	38.13	62.41
	MIN.	-55.86	-51.31	-55.08	-56.78	-65.94	-65.65
	RMS	13.90	12.57	13.03	13.57	15.69	20.73
	RMS(L)	13.57	12.16	12.70	13.22	15.39	17.87
	RMS(H)	3.04	3.18	2.94	3.03	3.01	10.51
HEAVE: (FT)							
	MEAN	1.86	0.70	3.13	2.16	2.12	4.25
	MAX.	22.41	26.65	30.26	27.22	30.89	38.83
	MIN.	-19.52	-19.29	-18.97	-13.64	-12.54	-15.14
	RMS	5.91	5.96	6.82	6.37	5.38	6.28
	RMS(L)	4.58	4.59	5.64	5.13	3.86	4.73
	RMS(H)	3.73	3.80	3.84	3.78	3.75	4.13
PITCH: DEG)							
	MEAN	-0.51	-0.17	-0.32	-0.85	-1.51	-2.97
	MAX.	4.15	7.12	7.11	5.51	6.02	4.06
	MIN.	-8.10	-6.38	-8.82	-9.37	-13.15	-22.54
	RMS	1.60	1.44	2.36	2.31	2.89	4.64
	RMS(L)	1.17	0.99	2.10	2.02	2.67	3.48
	RMS(H)	1.08	1.05	1.08	1.10	1.09	3.07
JOINT 1 TSN: (KIPS)							
	MEAN	1818.33		1510.56	1608.65	1694.56	
	MAX.	2820.74		2704.02	2688.46	2474.47	
	MIN.	494.17		23.41	350.22	894.90	
	RMS	332.22		423.97	313.30	260.63	
	RMS(L)	288.06		376.21	288.40	224.11	
	RMS(H)	165.50		195.50	122.40	133.07	
JOINT 2 TSN: (KIPS)							
	MEAN	1819.27		1425.32	1534.13	1686.86	
	MAX.	2753.35		2528.20	2251.10	2309.98	
	MIN.	661.20		103.53	636.96	820.54	
	RMS	267.60		348.53	236.40	211.00	
	RMS(L)	225.38		299.43	217.20	177.36	
	RMS(H)	144.28		178.36	93.32	114.30	
MOOR 1 TSN: (KIPS)							
	MEAN	465.27	346.84	398.21	406.44	404.16	474.58
	MAX.	1424.88	1065.92	1432.21	1336.97	1545.76	1531.11
	MIN.	139.19	120.88	135.53	109.89	76.92	95.24
	RMS	169.17	105.00	127.99	141.13	171.64	200.50
	RMS(L)	156.74	96.81	119.59	130.92	162.08	189.68
	RMS(H)	63.65	40.65	45.61	52.72	56.50	64.99

CHAPTER 7 COST ESTIMATE AND SCHEDULE

The cost estimate and fabrication schedule was not completed because the work was stopped by customer order prior to completion of CLIN 0006.

CHAPTER 8 CONCLUSIONS

In this conceptual study, an articulated stable ocean platform (ASOP) was designed with a fuel storage capability of 1 million barrels. The platform was also designed to support a topside up to 12,000 kips in total weight. In the hull design, more than eighty percent of the volume for fuel storage was designed to be pressure compensated tanks to reduce the structural size and steel weight. In addition, by pumping at a fixed ratio between pressure compensated and uncompensated tanks, the draft of the platform would remain unchanged at any loading condition without adjusting the ballast. This greatly simplified the operations and allowed the platform to continue other activities while loading and off-loading, such as oil drilling and/or production, which has high restrictions in draft changes.

The study shows that the ASOP has adequate stability and satisfies the stability requirement of the certifying authorities (US Coast Guard, American Bureau of Shipping). Both numerical analysis and model test showed that the ASOP offers exceptional motion response characteristics in all its degrees of freedom. This is evident from Table 8.1 which illustrates the ASOP motions in comparison with a typical surface type production and storage vessel. In terms of platform motion response, the ASOP is capable of operating in more severe weather conditions than a conventional surface vessel type platform.

In the numerical analysis, the articulation of the buoys complicated the analysis by allowing relative motion between the buoys and the hull. Instead of traditional single rigid body analysis for the floating platform, a seven body (six buoys and the hull) coupled analysis was needed for the ASOP. The study showed that the computer software MOSES was capable of performing multi-body analysis for the ASOP, and the numerical results in general agreed with the model test. In regular wave analysis, there was very good agreement between numerical and model test results in heave motion, universal joint force and mooring tension. The surge and pitch motions were slightly over predicted numerically but on the conservative side. In random wave analysis, the wave frequency motions and forces of the ASOP agreed with the model test results but there was a discrepancy in the slow drift motions. Numerical tools need to be improved in this respect to more accurately predict the nonlinear wave forces.

Both numerical analysis and model tests showed that the articulated buoys have no clear advantage over fixed buoys in the global motion of the ASOP. The original thought that articulation reduced the wave forces transmitted to the hull and hence reduced the motion of the ASOP was not supported by analysis or model test. The study showed that the majority of the wave forces were acting on the main hull itself which has more than 90 percent of the total displaced volume. Therefore, the reduction of forces by using articulation did not significantly improve the motion of the platform. Furthermore, the analysis and model test showed that compared to the fixed buoy case, using articulations increased the slow drift motions of the ASOP in random waves. The large rotational motion of the buoys created more nonlinear forces at the joints and caused large drift motions. The study also indicated that using spring connected buoys, or changing the buoy shape could further reduce the force transmitted from the buoys to the hull, but their influence on the motion of the platform and mooring line tension was insignificant.

The study also indicated that the introduction of articulations complicated the hydrostatic stability of the platform. Figure 8.1 is a comparison of stability of the ASOP between articulated and fixed buoys. The righting moment of the ASOP was greatly reduced due to the unique behavior of the articulated buoys. In order to have adequate stability, a larger initial stability (metacenter height) was required. Also, the loss of a buoy due to universal joint failure or complete buoyancy loss may cause serious stability problems. Damaged stability was the governing factor in determination of the size of the articulated buoys.

In conclusion, this conceptual study indicated that the fuel storage ASOP is a viable concept. Its large storage capability and exceptional motion characteristics allow many applications both in civil and military purpose. However, the introduction of articulation has no clear benefit over fixed buoys (simple columns) in reducing the motion of the platform. Therefore, the same platform with fixed columns instead of articulated buoys could be a more practical design. Figure 8.2 shows a similar platform to the ASOP with fixed columns instead of articulated buoys. This storage platform concept shows merit and should be developed further.

Although the articulation does not show clear advantage in the fuel storage ASOP, it may improve the motion of a more mobile catamaran type ASOP (non-storage vessel). Figure 8.3 is a concept drawing of the platform with articulated buoys (the catamaran ASOP). Unlike the storage ASOP, the displacement of the buoys has a much higher percentage in the total displacement and the wave forces on the buoys are significant. Therefore, reduction of the wave forces transmitted from buoys using articulation could possibly effectively improve the motion of the platform. Evaluation of the catamaran version of the

ASOP concept is not in the scope of this study, however this concept may be worth investigating further.

Table 8.1 Comparison of standard deviation of motion in 100 year storm

(Significant wave height = 39 ft)

	SURGE (FT)	HEAVE (FT)	PITCH (DEG)
ASOP	13.90	5.90	1.9
FPSO*	29.53	11.15	4.1

* A turret moored 102,500 DWT tanker system. Test results are from Applied Ocean Research 0141-1187/92

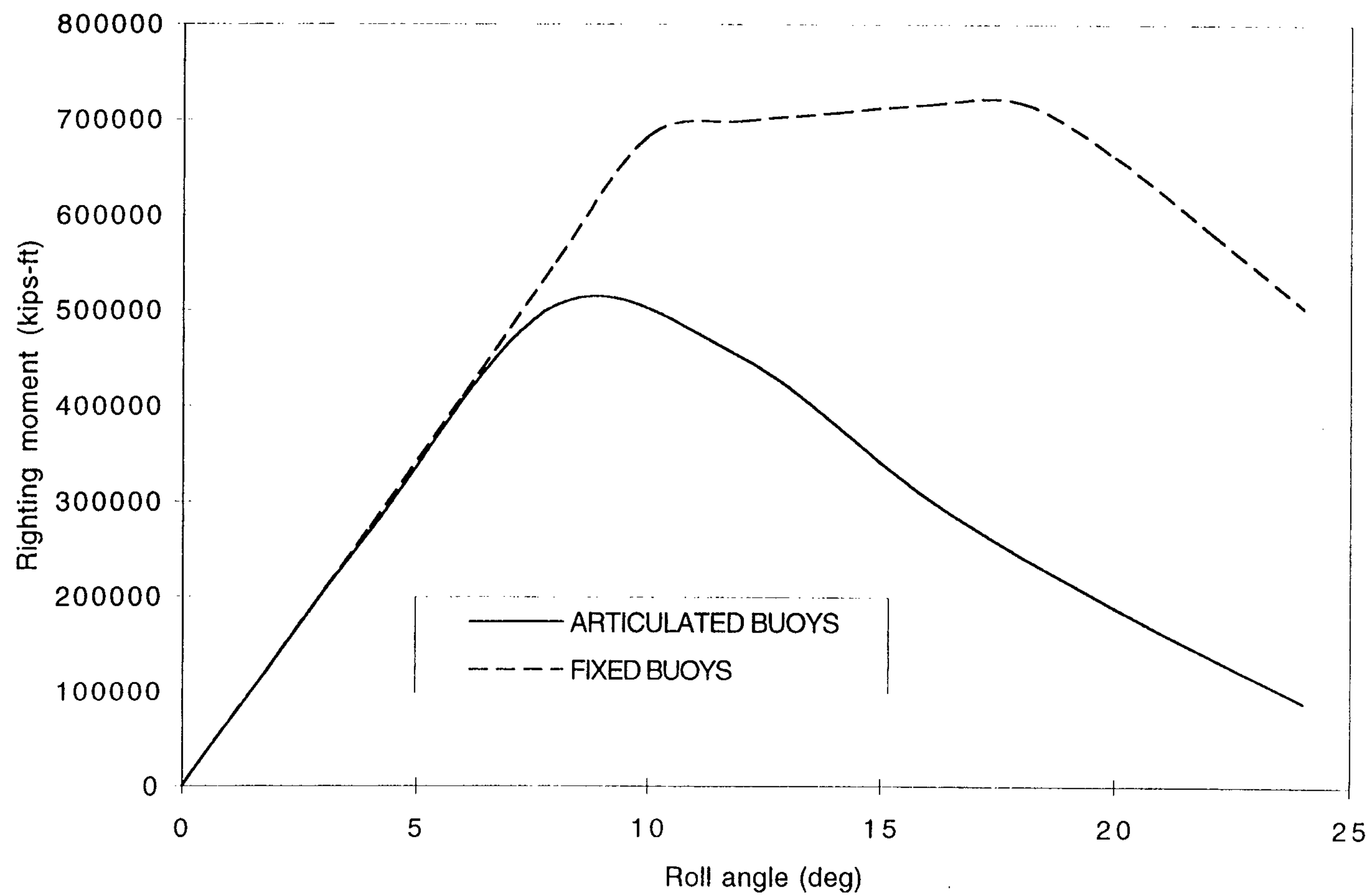


Figure 8.1 Righting moment of the ASOP with fixed buoys and articulated buoys

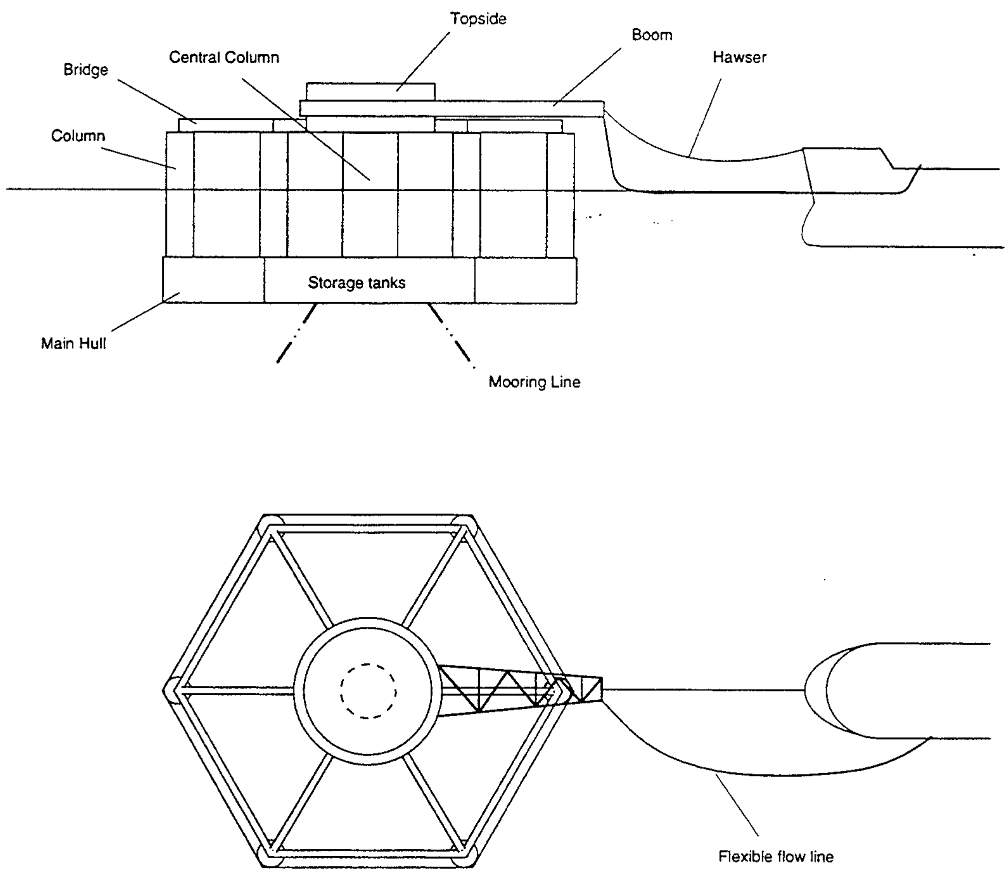


Figure 8.2 A column stabilized storage and production platform

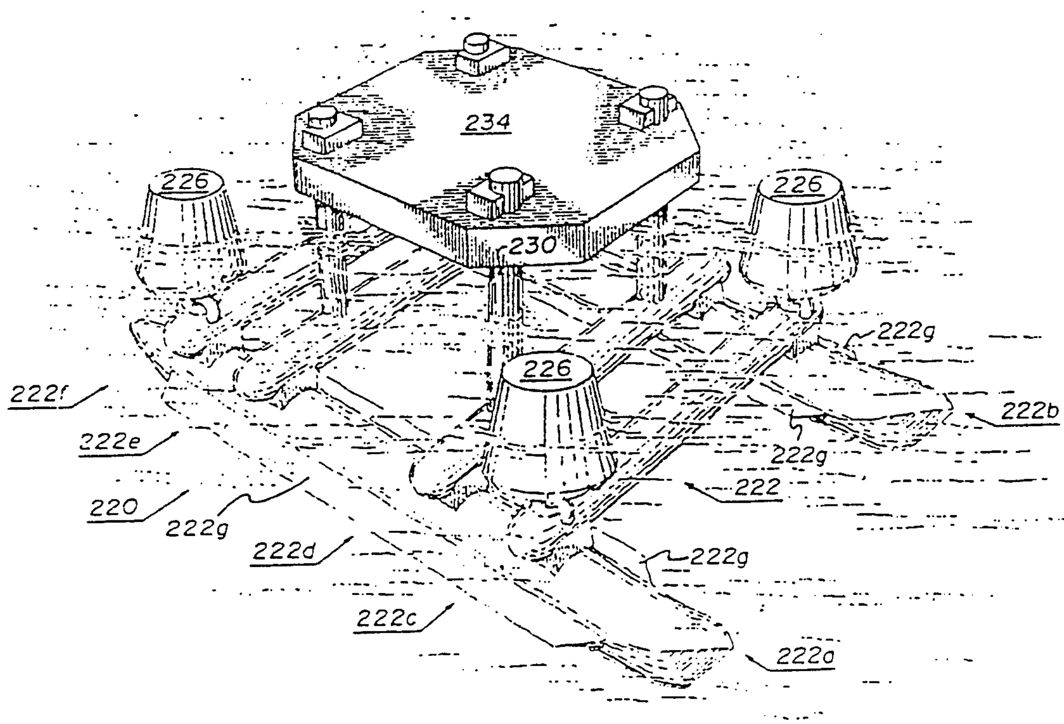


Figure 8.3 A catamaran type ASOP